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on

ANALYSIS OF THE EFFECTIVENESS
OF INDUSTRIAL R&D
(Report No. BCL-OA-TFR-76-8)

by

W. Halder Fisher, Herbert S. Kleiman,
John L. Moore, and Mark B. Triplett

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EXECUTIVE SUMMARY

The research was conducted in two parts. The first part, entitled "Examination of Some Critical Aspects of the Cost Effectiveness of R&D Expenditures", provides information concerning the criteria utilized by private industry in evaluating and selecting proposed Research and Development projects for implementation, and also in determining which R&D facilities are to be acquired. Two separate approaches were followed: (1) a literature search was made concerning R&D management and related topics, and (2) a group of knowledgeable persons was interviewed to obtain their expert judgment about the criteria known to be used in R&D-related decisions. The second part of the research, entitled "State-of-the-Art Review Assessing the Role of R&D in Economic Growth", identifies the conceptual and practical issues inherent in any quantitative analysis of the contribution of R&D to economic growth in order to assist NASA in developing approaches for analyzing the economic implication of its own R&D efforts.

Part I: Cost Effectiveness of R&D Expenditures

It had been hoped that quantitative case-by-case information might be gathered concerning the costs, expected benefits, and realized benefits to industry of acquiring and using specific R&D facilities. In their most direct and oversimplified form, the following inquiries were made of the human and documentary sources:

- What was the R&D setting -- i.e., what research barriers needed to be overcome and what facilities were expected to overcome them?
- What level of costs was associated with the new R&D facilities?
- What volume of benefits (sales, profits, public services, etc.) was expected as justification for assuming that cost?
- What volume of benefits actually was realized?

It soon became apparent that these questions could not be directly answered on a case-by-case basis. For this reason our searches were directed toward the two broader questions:

- What criteria are applied (or were applied, in any specific cases) in evaluating proposed R&D projects and in selecting the ones to be carried out?

- What were the impacts actually experienced after undertaking the chosen projects?

As a result of the literature search and the personal interviews a great deal of information has been brought together that bears on these matters. The more important of these findings and further conclusions based upon them can be briefly grouped in the following scheme.

General Criteria

- Business applies criteria of evaluation and selection more to the whole proposed R&D project than to the proposed acquisition of R&D facilities.

- In general these criteria are more likely to be qualitative than quantitative.

- Increasingly over time, business criteria relate to profitability, to the firm's existing products and markets, and to very short-term futures. As the proposed project departs from this threefold context it is less and less likely to be approved.

Criteria for R&D Facilities

- The most telling business argument for acquiring a given R&D facility is defensive -- i.e., that without it the firm cannot compete (or will compete less effectively) in its current markets.

- Management must be convinced that the proposed facility will lower costs, increase productivity and lead to higher profits. The promise of new knowledge has little if any value.

- To the extent that purely quantitative criteria are identifiable, new R&D facilities apparently should be able to pay for themselves in no more than five years, preferably in one or two years.

- Although industry does consider contributions to the public good as some justification for facilities acquisition, this criterion ranks far below contributions to profitability.

Industrial R&D and the National Economy

- Industry performs about 70 percent of all U.S. R&D, 43 percentage points of which it funds (and therefore controls) and 27 percentage points of which is funded by the Federal Government (and therefore only partly controlled by industry).
- The R&D projects and facilities that are both funded and performed by industry are subject to all the above criteria; the rest are justified by governmental criteria.
- In dealing with economic growth, there is a wide-spread tendency to oversimplify by generalizing, "Technology leads to economic growth, R&D leads to technology, therefore all R&D leads to economic growth".
- Economic growth may be a statistical, rather than a real phenomenon, depending on definitions.
- Although R&D may lead to economic growth, it may also have the opposite effect. A more correct statement is that some, but not all, technologies can make a net contribution to economic growth.
- The "market test" does not measure contribution to growth. The fact that a given R&D project or facility is chosen because of its short-term profitability does not mean that it will be socially desirable in the long run.
- Additional points that must be kept in mind are:
 - Regardless of attractiveness, the most productive R&D project is the one that discovers and puts into place the last piece of the technological jigsaw puzzle;
 - The time lags between R&D effort and technological pay-offs may span days, years, decades, or centuries.
- There are positive long-term relationships among industrial R&D, technology, and economic growth, but they are extremely complex.

Part II: The Role of R&D in Economic Growth

Studies of economic growth have focused on the aggregate contributions of capital and labor and of advances in factor productivity to the growth of output. Specific studies of the role of R&D in economic growth have been limited to industry analyses with the exception of one recent attempt at macroeconomic analysis.

Economic growth can be defined as an increase in the available per capita quantity of real goods and services. Historically, until the last two centuries, economic growth proceeded through expansion and improvements in the labor force, accumulation of capital, slow advances

in capital technology, advances in knowledge and the state of the art of materials, and through expansion to new virgin sources of natural resource supply. Recent decades, however, have witnessed profound and rapid changes in our production technologies, materials, and array of available products. Technical advances in materials so far have tended to offset diminishing returns in many natural resources, either through direct substitutions or through the beneficiation of low quality supplies. Advances in the state of the art of materials and capital equipment have permitted increasing substitution of capital and fossil fuel-derived energy for human or animal labor. With these fundamental changes have come rising standards of living accompanied, however, by increasing social costs in the form of environmental deterioration and stress on traditional cultural and social values.

Organized research and development has been viewed as a potential influence for economic growth only during the last three or four decades. Its specific quantitative role in any aggregate sense has been difficult or impossible to estimate because of conceptual and/or data-related limitations. For this reason, most studies of these relationships have focused on the influence on aggregate factor productivity of advances in knowledge or of technical change. Production factors traditionally--and incorrectly--are defined as land, labor, and capital.^{*} Standard estimating techniques have attempted to measure the contribution of technology to economic growth in terms of the residual growth that is unexplained after accounting for all growth attributable to increases in the inputs of capital and labor. These estimates range from .1 percentage point to 2.3 percentage points of observed growth being attributable to technological change. In addition to the serious error introduced by the faulty definition of productive factors, however, all quantitative estimates are subject to model specification and measurement problems, and this seriously limits the usefulness of any specific set of quantitative estimates. The general importance for economic growth of advances in the state of knowledge seems nevertheless to be indicated by the studies that have been conducted.

* This traditional definition increasingly is being replaced by energy, material, and know-how, with the recognition that land/labor/capital represent elements of income-distribution (i.e., the basis for claims against the value of output).

While a number of studies have focused specifically on the role of R&D, these efforts generally have been confined to inter- and intra-industry studies. As a group, they show a relatively high elasticity of output with respect to R&D expenditures. Whether the statistical associations show causality or correspondence with other industry characteristics still is not clear. The estimate of a 43 percent rate of return to NASA R&D was obtained in the only macroeconomic study dealing directly with R&D. These results are limited, however, by the questionable validity both of the model's definition and specification, and by the weakness of extrapolating historical relationships.

What emerges from thorough recent reviews of the empirical literature is a range of findings--all achieved by essentially the same methodology--that is so broad as to be meaningless.. For instance, the Chase Econometrics study of the growth in GNP that can be expected to flow from NASA's R&D activities found that for every dollar of NASA-supported R&D there would be \$4.26 of new GNP during 1975-84. When similar results obtained by other investigators have been reduced to approximately comparable form, they imply a range of incremental GNP from about \$0.33 to \$7.54.

It is clear that better data and better alternative methodologies are needed if we are ever to understand the links among R&D activity, innovation, technology diffusion, factor productivity, and growth in per capita real GNP. There is also a serious need for broader and more scientific definitions and conceptual frameworks within which to deal with economic growth in terms of natural resources, social factors, and the implications of environmental deterioration.

Three different approaches are suggested for use by NASA in understanding the economic consequences of its own R&D activity:

- The first would utilize detailed studies of selected past NASA innovations to explore in micro-detail the ways in which they were used in industrial innovations and the economic consequences of those uses.

- The second would adopt the benefit-cost framework proposed by Thurow as a means of judgmentally establishing ranges of the potential benefits and costs of NASA activities. This would greatly strengthen the R&D policymaking capabilities of the agency.

- The third would incorporate an R&D sector into a modified interindustry model that could be used to simulate the effects of R&D spending on technology and the economic impacts of R&D-induced technological changes. Unfortunately, most readily available interindustry (I/O) tables have not been constructed in a way that makes them usable for technology simulations.

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ANALYSIS OF THE EFFECTIVENESS OF INDUSTRIAL R&D

PART I:

EXAMINATION OF SOME CRITICAL ASPECTS OF THE COST EFFECTIVENESS OF R&D EXPENDITURES

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INTRODUCTION

This is the Part I report of a task involving analysis of the effectiveness of industrial R&D conducted under Contract NASw-2800, "NASA Applications Studies -- New Initiatives". The task takes the form of a two-part effort: Part I involving the definition of the problem and an attempt to examine it in preliminary terms through the use of secondary data; and Part II addressed to a more complete, perhaps primary, analysis.

The problem itself relates to the decision-making aspects of industrial research and development (R&D). In undertaking R&D activities, the private economy must apply criteria of cost-effectiveness, first to the R&D process itself (in contrast with other alternative uses of the same resources), and second to alternative R&D projects. NASA needs to know as much as possible about the business decisions that will determine the extent to which the business community will support and use NASA-provided research facilities. In order to make effective decisions with respect to the private economy, there must be a clear understanding of both the criteria and the intellectual processes that are involved.

As originally proposed, this research task was addressed entirely to the acquisition of R&D capabilities, and particularly to the achievement of new levels of capability -- i.e., to the use of tools whose precision is one or more orders of magnitude better than that of their predecessors. Emphasis was directed toward decisions that involve new thresholds of capability, such as the shift from optical to electron microscopy. Quite early in the project, however, it was recognized that while such sharp changes of capabilities were rather rare, many less dramatic ones also provide valuable insights into private sector decision making. The scope of the research was therefore widened, although the general methodology remained as proposed:

the combination of a literature search and a series of discussions with selected knowledgeable persons (1) to identify several cases involving upward steps in capability, (2) to obtain indications of the cost of taking such steps, and (3) to at least partially estimate the flow of benefits from them.

The Conceptual Framework

Conceptually, the R&D process is viewed herein as an attempt to bring together a critical mass of technical knowledge that will enable the firm or the society to pass over a threshold. In many instances the lack of this knowledge may constitute an absolute barrier which, until overcome, brings progress in particular directions to a complete halt. In other, less dramatic, cases progress may be slowed, costs may remain unattractively high, or public and private benefits may fall below desired levels.

In the private sector, where profits provide a major incentive for innovation, considerations of cost-effectiveness usually are among the more common criteria of choice. Presented with two alternative uses of the same resources, a businessman usually will choose the one which promises more profit per dollar of cost. While considerations of profits may not be as influential in public sector decisions, implicit benefits (of some kind) per dollar of cost are taken into account. Decisions concerning R&D -- either the acquisition of new R&D capabilities or the undertaking of particular projects -- may be made with reference to the private economy by either private or public agencies. It is this fact that makes it so worthwhile that the private sector's criteria be understood and applied.

Organization of This Report

The next section of this report examines the research problem in greater detail, providing both the definitional framework and the philosophical background of our activity. This is followed by a rather detailed discussion of the methodology and procedures used in carrying out the research. The findings of the literature search are then summarized, as are those of the discussions with knowledgeable persons. Finally, built upon these findings are some further generalizations and conclusions that may be useful to governmental efforts to enhance the R&D facilities available to the private sector.

THE RESEARCH PROBLEM

Much of the R&D activity undertaken or funded by NASA tends to be justified directly or indirectly in terms of the facilities and/or knowledge that it makes available to the private sector; the rest is justified in terms of its contribution to the Federal Government's ability to provide particular collective services to the private sector. Thus, an extensive R&D program is justified, either directly or indirectly, in private-sector terms. Because it deals largely with the support of persons or of human artifacts in a remote and hostile environment, research projects undertaken by NASA generally tend to be exotic, specialized, and/or sophisticated. Almost by definition, only a relatively small proportion of the results of such R&D will be immediately applicable to mundane private sector problems -- although a much larger and richer contribution undoubtedly can be anticipated with the passage of time.

It is clear, therefore, that the criteria by which NASA makes its own R&D decisions may differ substantially from those generally applied by public and private agencies. This makes it necessary for us to examine the more general configuration of R&D decisions before taking up the details of the present research problem.

The R&D Decision

Generally speaking, there are three intellectual environments within which R&D decisions are made: governmental, industrial, and academic. These three terms are employed in a generic, not a literal, sense. "Governmental" environments are service-oriented; governmental R&D is undertaken because of its social value, its contribution to national growth, or because it makes a collective contribution to the public good (e.g., defense). The R&D work may be funded by the private sector or performed in an academic or industrial setting; nevertheless, the R&D decision is the kind typically made in a government agency. It will be essentially a pragmatic one, made in terms of cost-effectiveness, but "effectiveness" will have a clearly social-service dimension.

"Industrial" R&D may be performed or funded in government or in the academic community, but it will be undertaken because it enhances the

profitability of one or more industrial enterprises. The industrial R&D decision also is pragmatic, but its pragmatism is directed toward lowering costs or enhancing productivity and/or profitability in some specific line of enterprise.

Again, regardless of its actual location, "academic" R&D (also termed "basic research") is not pragmatic in motivation. It satisfies curiosity or adds to fundamental knowledge -- there is no other purpose for which the decision to pursue the R&D is made. In the longer term, academic research may make a tremendous contribution to society or to the profitability of particular enterprises. But when it is first undertaken, no such pragmatism enters into the decision.

In summary, we can say that there are three main classes of R&D decisions. Two involve pragmatic elements that can be expressed in terms of cost-effectiveness; the third does not. However, in the case of the first two, the nature of their respective pragmatisms differs. Thus, there are three kinds of justifications which may be required and three kinds of criteria which may be applied when deciding whether or not to acquire particular new capabilities.

Elements of the R&D Decision

What we have termed the R&D decision is composed of several elements. As has been indicated, every R&D project is undertaken for a purpose. Conventionally, a project will be classified -- depending on the purpose -- as being basic research, applied research, or development. The purpose establishes the criteria for determining which of several alternative projects will be undertaken. In order to carry out any R&D project, capital (plant and equipment) must be available and expenses (for labor and other inputs) must be met. The R&D decision therefore involves a series of choices, each in terms of its relevant criteria, that will determine (1) exactly what R&D activities will be carried out, (2) exactly which capabilities or facilities will be acquired or utilized, and (3) what level of expenses will be funded. At this point, we need to examine these elements and to delineate the framework within which the criteria themselves become meaningful.

The Kinds of R&D Activity*

"Research and Development" is now a specific term of the arts that embraces the two main activities, scientific research and experimental development. Scientific research is defined as the use of accepted scientific method to discover new knowledge concerning natural relationships and processes. As shown below, it is usually subdivided into basic and applied research. Experimental development, on the other hand, is defined to consist of the application of scientific knowledge (discovered in the past by research) in the design and development of new or significantly modified products or processes.

Basic research is defined by the National Science Foundation as research undertaken solely for the purpose of satisfying curiosity or adding to knowledge. As indicated above, no matter where it is undertaken the immediate situation may be characterized as "academic". The criteria by which choices are made among alternative basic research projects are highly personal with the researcher. They are not formally pragmatic.** If it is at all possible to apply criteria of cost-effectiveness to basic research, the effectiveness is intangible and can consist only of the satisfaction derived by the researcher.

Applied research differs from basic research only in its purpose. It involves the deliberate increase of knowledge in specific scientific areas for the purpose of aiding in the development of new/modified products

* These definitions are based on those used by the National Science Foundation in its regular series of "Surveys of Science Resources". See, e.g., National Patterns of R&D Resources: Funds and Manpower in the United States, 1953-1975 (NSF 75-307, April 1975) p. 15.

** Pragmatic personal (rather than industrial) criteria often do in fact enter into "academic" R&D decisions. For example, many academicians often undertake particular research projects to enhance their job tenure or to gain promotion. In other instances a professor may be primarily motivated by a need to establish a reputation in a field of specialization. Nevertheless, the knowledge is not sought for an economic or pragmatic purpose -- it is the seeking process which has the pragmatic purpose.

or processes. In other words, applied research is expected to contribute to a particular end other than that of "pure" science. Regardless of where it is undertaken, its purpose is pragmatic; it is expected to provide either governmental or industrial benefits; and it will almost always be subject to some kind of cost-effectiveness criteria.

Development can be governmental in its purpose -- as, for instance, the development of a weapon system -- but it is also viewed as a normal activity of the industrial sector. Generally speaking, the costs associated with development constitute the major portion of total R&D costs, for which reason the development process will be more strictly subjected to cost-effectiveness criteria than either basic or applied research.

R&D Capital

A major kind of "R&D facility" is the plant and/or equipment employed in the conduct of R&D work, in contrast to the expertise of the scientists, engineers and supporting staff who do the work. As originally planned, it was hoped that this research project would uncover sufficient information about the acquisitions of R&D capital for the entire project to be confined to this subject. This has not been the case.

The electron microscope, chosen earlier to illustrate our conception of this problem, has proved to be an almost perfect -- but perhaps unique -- illustration. It represents a true quantum jump in research capability, permitting otherwise impossible degrees of resolution. It is so expensive that it would seldom constitute a routine addition to equipment. And we can easily visualize particular lines of research reaching a dead end at the best attainable levels of optical magnification. We will discuss this "ideal" case of capital facility in a later section. Unfortunately, there seem to be few others that fit our conceptualization as neatly.

Human R&D Facilities

The other kind of facility or capability, lack of which might prove a barrier to further R&D progress, is embodied in persons. It is quite

conceivable that there might be one or more individuals, either the acknowledged authorities on particular fields of science or persons of unique leadership capabilities, around whom a revitalized research program might be built. However, to hire such persons and provide the environmental and staff support that would make them fully effective could prove quite costly. This too would qualify as a case to be studied within the conceptual framework of the present research task.

The Decision Itself

Given a typical industrial or governmental R&D situation -- i.e., one to which definite criteria of cost-effectiveness could be applied -- we can establish a standard scenario. The Research Director would propose, in order to surmount a particular high priority threshold, that a specified capital or staff facility be acquired. This acquisition would have an estimated price tag too large to allow its treatment as a routine expenditure. Therefore funding would have to be provided or approved by a financially oriented (i.e., nonresearch) Treasurer, Comptroller, or business executive. This official would have to be convinced that the proposed expenditure represented the best use (in terms of the institution's own goals) for relatively scarce financial resources.

Thus, we come back to the central question addressed by this research task: What is the relationship between the cost of acquiring the facility or capability, on the one hand, and the stream of expected benefits by which that acquisition is being justified? The ultimate decision maker is viewed as being relatively hard-nosed, businesslike, and unsympathetic to R&D as such, and therefore as having much more pragmatic criteria that must be met. What relative level of expected returns constitutes a justification in his eyes?

Finally, assuming that the criteria are met, the financial manager accepts the proposed justification, and the new facility is acquired and put to use -- what is the actual realization? Were the promised benefits realized or not, and to what degree? We would expect to encounter both successes and failures; and it would be hoped that cases of each kind might be

found and examined. In this way we should gain better insights than we now possess into the business decision processes that determine the levels of financial support industry might provide NASA in return for the use of new and unusual R&D capabilities.

The Problem Restated

Using readily available personal and secondary sources, we have undertaken to answer a series of major and associated questions about each of several identified cases.

The Major Questions

- (1) What was the technical threshold under consideration?
- (2) What was the capability by which the threshold was expected to be surmounted?
- (3) What level of costs was associated with the new capability?
- (4) What volume of benefits (sales, profits, public services, etc.) was promised in justification for acquiring the new capability?
- (5) After the fact, what volume of benefits was actually attributable to the new capability?
- (6) What other unexpected R&D opportunities were opened up by the acquisition of the new capability?

Other Associated Questions

There is a wide range of other matters in which NASA would be expected to have a general interest. Among them, with no particular claim to order of priority, would be:

- (1) Did the group or agency that provided (or invented or developed) the new capability know in advance that it would be needed or used in this fashion?
- (2) How did the particular users of the new capability learn that it was available?
- (3) Did those with the problem advertise their need?
- (4) Was the capability new in an absolute sense or was it merely new for this application?
- (5) Was the capability developed internally by this user or did it come from outside?

- (6) Was the capability originally viewed as very specific or as being broadly useful?
- (7) Was the new capability viewed a priori as a means of "breaking a logjam" or more as a means of accelerating progress?
- (8) Was the technical threshold against which the new capability was applied viewed as a problem to be overcome or as an opportunity to be exploited?
- (9) Was the technical threshold viewed as being the last barrier to be overcome or was it only one of a series, all of which had to be surmounted to achieve success?

There were many other questions which could have been asked. However, with relatively limited time and staff resources, more questions probably would have been redundant. This is especially true since it seemed unlikely that most available cases would provide answers to all the listed questions.

THE RESEARCH PROCEDURES FOR THIS TASK

This section is intended to provide a transition from the conceptual framework of the study (in the previous chapter) into the findings (the two sections that follow). It does this by focusing almost entirely on the more mechanical aspects of the study: What and how much was done. In addition, we conclude this section with a brief description of the kinds of information that can be expected from the findings themselves.

Methodological Alternatives

There are three types of methodologies that can be used to attack a problem of this kind: a search of the literature, an interview-survey of persons who would be well informed about past situations involving decisions to create or acquire expensive R&D facilities, or a statistical survey of firms and other organizations to determine their experiences in decisions of this kind. Also, it would be possible to proceed by a combination of any two or all three of these approaches.

The Literature Search

There is a growing literature addressed to motivations for R&D and the results of R&D. Much of this will be classified under such key words and phrases as research management, innovation, or technological change; but much of it will also be classified as studies of the particular industries in which the R&D was undertaken. The Journal of Economic Literature, for example, regularly lists, classifies, abstracts, and/or annotates the content of several hundred professional journals related to economics, as well as reviewing most relevant books as they are published.

There is a wide range of business or trade-oriented periodicals (e.g., Fortune, R&D, Innovations) which also carry factual articles related to the R&D decision process. The contents of these and a large number of other general periodicals are indexed and classified in The Reader's Guide to Periodical Literature.

In the final analysis, any search of the literature consists of the systematic use of guides to compile a listing of potentially useful titles (both books and articles). These are then examined to determine if they are in fact relevant to the subject, thereby further screening the original universe. Finally, the most relevant sources are studied and/or digested into findings.

Personal Interviews

The use of informed personal sources proceeds in essentially the same way as does a literature search. There is, however, one obvious difference in that there is no centralized source listing of persons who both know of the kinds of cases sought and are willing to talk about them. If particular scientific disciplines are thought to be likely sources of relevant cases -- e.g., lasers, electron microscopes, cryogenics -- then listings of experts in those fields are available and can be consulted. Generally speaking, especially where a broad range of disciplines is to be covered, the best procedure is to work by personal referral, with each potential interviewee becoming in turn a source of other suggested persons.

In a technologically oriented organization such as Battelle, the search for interviewees can go forward quite easily. Not only do members of the professional staff know of many other firms or persons which might provide cases of the R&D decisions being examined, but Battelle itself continually makes many such decisions.

Another need when using personal knowledge about R&D facility decisions involves the generation of a "shopping list" of potentially fruitful cases. It is obvious that generalists in the fields of R&D management and/or technological innovation would provide above-average beginning points for the development of such a list. Battelle, being one of the larger institutions in the field of contract R&D, has among its management and research staffs many such persons. These resources were drawn upon in the present project.

After lists of interviewees and potential cases have been drawn up, the interviews themselves will be rather straightforward. Questions

would be asked such as those given at the end of the previous section, and the answers recorded and collated. These answers, plus further discussions by the experts of related topics, would become the basis of the ultimate findings. Ultimately, they must be woven together with findings from the other methodologies into the final generalizations of the project.

Surveys of Industrial/Institutional Cases

If a sampling of firms, government agencies or other R&D-oriented organizations can be drawn and persuaded to cooperate, probably more precise quantifications can be obtained of the cost-effectiveness of the selected R&D facilities than are otherwise available. This is true because the survey can combine the experience and expertise of the decision makers themselves with the recorded accounts of costs and benefits. When this project was originally proposed, we assumed that it might ultimately lead to such a field survey of industry experience. However, no such survey was contemplated as part of the project.

Summary

Although there are three methodological approaches that could have been used in this research task, one was not used because of its high cost in time and money. The approach that has been chosen and applied combines a search of the literature with a series of interviews with knowledgeable persons. Many of these persons are members of the Battelle management and research staffs, but others are employed outside Battelle.

The remainder of this section is devoted to brief descriptions of the procedures, levels of effort and kinds of findings associated with the adopted approaches. The two following sections briefly summarize the findings.

The Literature Search

The following three main sources of titles were used for this search:

- (1) The Reader's Guide to Periodical Literature, 1975 ff.
- (2) The Journal of Economic Literature, 1969 ff.
- (3) The Government Reports Index, 1973 ff.

The topics searched for leads included "Research", "Technology Development", "Technological Innovations", "Technology Transfer", "Technology Utilization", "Industry Studies", and obvious variants. Among the periodicals which reappeared frequently under these topics, several seemed especially promising and were examined in their entirety for varying periods of time:

- (1) The IEEE Transactions on Engineering Management (monthly) 1972-74
- (2) Research Management (semimonthly) 1970-76
- (3) Technology Review (monthly) 1973-76
- (4) Science (weekly) 1972-76
- (5) Technology Forecasts and Technology Surveys (monthly) 1973-76
- (6) Research/Development (monthly) 1975-76
- (7) Industrial Research (monthly) 1975-76

The initial search brought together a group of titles that appeared sufficiently relevant to warrant further examination. These included approximately

- 150 articles and monographs
- 40 books
- 20 Government reports.

Of these, further examination reduced the three categories to about 30, 10, and 10, respectively. The general substance gleaned from this literature is summarized later in this report.

Personal Interviews

Most of the interviews were face-to-face; a few were conducted by telephone; but all were preceded by telephone conversations which both made

arrangements and oriented the expert with respect to the information being sought. As was pointed out earlier, Battelle's Columbus Laboratories supplied a large number of the management and research experts interviewed. The following disciplinary fields or research facilities were represented:

Fields - Physics
 Spectroscopy
 Microscopy
 Chromatography
 Biomedical
 General engineering

Facilities - Electron microscopes
 Computers
 Animal facilities
 "Clean room" facilities
 Lasers

Outside Battelle-Columbus, representatives and/or staff members were interviewed at three companies operating in fields of electronics, instrumentation, and computers; at three magazines in the fields of research and business management; and at three nonprofit organizations, one involved in support of innovation and licensing, one doing research for business management, and one a trade association for research businesses.

All the interviews were addressed to questions (derived from those set forth earlier) concerning (1) the criteria used in decisions concerning the acquisition of R&D facilities, either specific or in general; (2) comparisons between expected and realized performance of specified facilities; or (3) the business or intellectual environments within which R&D decisions usually are made. A summary of the findings of all these interviews is presented later in this report.

General Nature of the Findings

Briefly, the results of the literature search and the interviews appear compatible with each other and can be characterized collectively. There were no precise, highly quantified relationships or criteria which emerged. Even in situations where relatively hard-nosed business decisions occurred or would be expected, there is considerable allowance for

intangibles and for considerations of public benefits. Because (as has already been mentioned) research per se is a small element in the total costs of research and development, the acquisition of research facilities may not be subjected to criteria as strict as those applied in the selection of new product/process innovation programs.

More important in the final analysis, however, is the evidence that industrial R&D generally seems to be increasingly subjected to entirely different decision considerations than those that have applied for most of the postwar interval.

FINDINGS OF THE LITERATURE SEARCH*

As has already been indicated, the literature on this general subject has proved to be much broader and more generalized than are the central questions posed earlier in this report. Nevertheless, a great deal of attention has been paid to related issues from which we gain many useful insights.

These issues may be viewed as falling into two classes: factors which have an impact on the R&D decision to acquire new facilities; and factors that are affected by that new capability. Each of these classes may be further subdivided between those internal to and those external to the firm. A convenient framework embodying these considerations is depicted in Figure 1. This framework proved more adaptable to the nature of the literature than the questions as originally posed. It has therefore been adopted for this chapter.

Although there is no dearth of discussions of the R&D process, we were unable to find examples of studies that were sufficiently disaggregated to provide precisely the kinds of cases sought. The decision about the use of R&D funds was always in terms of total R&D efforts rather than of specific research tools. No cases were found which reported company detail sufficient to show the independent effects of each R&D facility. Therefore, it has been necessary to compile our findings for use in the development of guidelines or analogous rules which would apply in the desired situations. An effort has been made to restrict the presentation of these findings to points which apply to the primary focus of the study.

Also, the broad subject of R&D has been treated in the literature from many quite different points of view. Some of these are more directly relevant to the central questions of this study than others. For instance:

* The literature search itself was undertaken and an initial draft of findings was provided by Mr. Mark B. Triplett, Systems Analyst in Battelle's Economics and Management Systems Section.

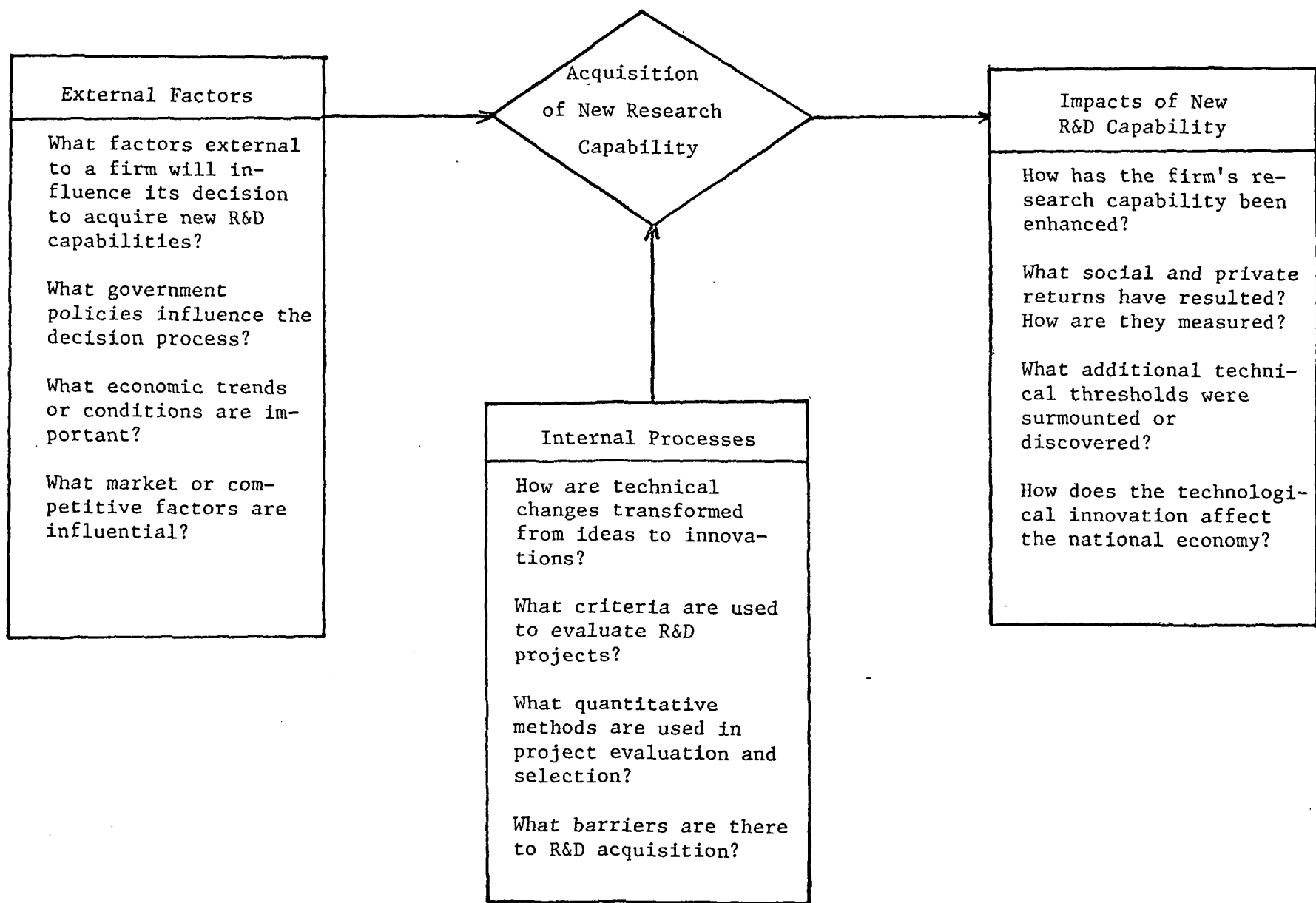


FIGURE 1. FRAMEWORK FOR THE LITERATURE SEARCH

The industrial research point of view tends to stress the availability of particular tools or devices that are useful in certain fields of R&D. Although some of these may be the kinds of R&D facilities that concern us, they are seldom treated in terms of their threshold-surmounting capabilities.

The economic point of view generally tends to emphasize the impact of R&D upon industrial and/or national economic growth. Although this is a measure of R&D effectiveness, it is seldom approached with the specificity implied in our study's conceptualization.

The R&D management point of view examines the R&D decision as an internal process of the firm. It is probably the most directly relevant viewpoint available for this study.

The technology point of view examines specific breakthroughs and innovations. It also examines problems of technological forecasting and technology assessment. While possibly relevant to our study, it seldom provides the degree of detail that we seek.

External Factors

Federal Actions

In recent years an increasing awareness has developed of the relationship between R&D expenditure and national economic growth. Recent industrial trends toward reductions in R&D activity are thought to have serious negative long-run implication for the national economy. A recent NSF report elaborates upon this view:

"R&D and other aspects of innovation are often cited as examples of areas where market and institutional imperfections exist (Council of Economic Advisors, 1972). Here, the inability of the sponsoring group to capture many of the benefits of R&D, as well as such factors as uncertainty, risk, and the need for large-scale investments, may lead private firms to invest less in R&D than would be efficient when viewed in a broader context. The same factors may lead private institutions to skew their investments away from basic or long-term research toward applied and short-term research and development. Therefore, if left completely in private hands there might be (1) insufficient R&D performed -- insufficient in the economic

efficiency sense that the total expected benefits from more R&D exceed the expected costs of more R&D -- and (2) R&D of inappropriate short versus long-term mix. If this is the case, government action may be appropriate and necessary to redress such market and institutional imperfections". (NSF, 1976)*

The concern, then, is to develop Federal policies that will stimulate R&D investment. Too little is known about the causal relationships in this problem area to allow the formulation of policy, so the Office of National R&D Assessment has sponsored several policy-oriented research projects on this and related problems.

The primary findings of these studies were:

- (1) The immediate problem is not so much insufficient Federal action to stimulate productivity growth as it is inadequate ability to evaluate the effectiveness of any Federal efforts.
- (2) Better data and a clearer understanding of productivity are needed.

With regard to Federal policies which in the near future would substantially change the incentives for R&D expenditure, there seems to be little evidence that such measures will be developed for the economy as a whole. However, specific classes of industrial research -- e.g., the development of new energy sources or the creation of pollution abatement devices -- are likely to benefit from Federal policy.

Market Factors

The relationship between R&D expenditure and marketing is fundamental to the entire industrial innovative process. Potential innovations which respond to clear needs in the marketplace are the ones most likely to gain the support of management. Competitive activity of other firms is also an important determinant of project support. Similar views are widely prevalent in the literature:

- (1) The decision process in a firm is strongly influenced by competitive R&D activities of other firms in the same industry (Utterback, 1974)
- (2) Innovation seems to be stimulated by expanding markets (Schmookler, 1966)

* Citations in parentheses are to the bibliography appended to this section (see page 32).

- (3) Innovations are frequently aimed at the rising costs of inputs, at cost reduction, or at process changes (Schmookler, 1966)
- (4) Technological change occurs primarily where there is a fairly clear short-term potential for profit (Utterback, 1974)
- (5) Innovations of great commercial significance are generally of the relatively low-cost, incremental type that results largely from continuous development efforts (Myers and Marquis, 1969)
- (6) About 60-80 percent of the important innovations in a large number of fields have been made in response to market demands or needs (various studies; summarized in Utterback, 1974).

Internal Processes

A substantial portion of the current and recent literature on R&D is being devoted to its management aspects. The issues now being explored in this connection are directly related to the process by which R&D capability is being acquired. It is in this field of the literature that quantitative methods for the evaluation, selection and control of R&D projects are beginning to emerge. Although no single method has yet been established as best, several similar lines of action have been examined and practiced. These methods will be presented following a brief discussion of essential definitions.

A workable scheme for categorizing the phases of the R&D or innovation process has been proposed (Dean, 1968):

- (1) Idea generation and handling
- (2) Project evaluation
- (3) Project selection
- (4) Project control
- (5) Project completion and termination.

Project evaluation and selection are the activities of greatest interest within the context of this study. They are closely related to each other, since, while project selection is limited to the actual selection processes, including the selection criteria, project evaluation covers methods and criteria for evaluating alternative proposed R&D efforts.

Efforts at the evaluation of proposals for R&D projects, either singly or alternatively, imply a rational approach. Quantitative evaluation methods obviously presume that rationality is inherent in the entire innovation process. This rationalistic view must, however, be balanced with a nonrationalistic approach, because irrational elements are the source of many limitations upon the R&D planning process (Schon, 1967). The basis for this viewpoint, according to Schon, is that:

Invention is a complex, social, nonrational process. It looks different from the inside than it does from the outside. One must continually replot the course of invention because it seldom follows according to plan.

Invention often works backwards from intriguing phenomena, rather than forward from well-defined objectives.

Invention is full of unanticipated twists and turns. It is a constant juggling of variables in response to problems and opportunities that are constantly being discovered along the way.

Need and technique determine each other in the course of development; neither is fully determined at the outset.

It is not always apparent ahead of time from which disciplines or technologies particular answers will come.

The purely rational approach, which would have to be modified somewhat to accommodate Schon's contribution, involves seven steps. We have no evidence that they have ever been applied in all their abstract "purity":

- (1) Determine overall company objectives and goals
- (2) Integrate all product research and marketing activity into management plans
- (3) Organize a system to facilitate getting ideas for products
- (4) Obtain, evaluate and select useful ideas and information
- (5) Design, build and test the product
- (6) Produce and market the product
- (7) Evaluate the product continuously.

From the point of view of the individual business firm, research activities can be categorized purposively into three broad classes. Since each of these categories serves a different corporate purpose, it must be evaluated in terms of different criteria. The several criteria tend to be implicit in the very natures of the categories, which are:

- (1) Supportive of existing business -- Research which is conducted in direct support of an existing business to maintain or improve its products, profitability, and/or its market and social acceptance
- (2) Exploratory research -- General long-range support of technology for the purpose of advancing knowledge of phenomena of general interest and for setting the stage for finding major new high-risk business projects*
- (3) New high-risk business projects -- Research conducted with the intention of developing a product, process, or market wherein the corporation has no direct manufacturing or marketing experience (Petersen, 1976; also paralleled or paraphrased in many other sources).

Evaluation

The evaluation phase is critical in that it involves the compilation of quantitative data describing important characteristics of proposed R&D projects. The management/R&D literature has several recent citations on this subject, but none refers to specific projects. Some, however, contain details concerning the evaluation procedures that have been used by various firms.

A particularly comprehensive source on this subject is (Dean, 1968) a compilation of responses by 40 firms to a questionnaire administered by the American Management Association. Detailed narratives concerning the project evaluation processes in 13 companies are included in the study. Table 1, abstracted from the report, provides an analysis of the factors used by respondent firms in their R&D evaluation.

As a result of the data reported to him, Dean was able to divide the factors affecting R&D proposal evaluation into two main groups, intangible factors and profitability factors. The "intangible" factors are those upon which no dollar value can be placed. However, they are very important in determining the company's ability as a whole to cope with the introduction of the proposed new product. These factors include the firm's capabilities in marketing, product engineering, and production, as well as the market durability and growth potentials of the product.

* This seems to be restating what has previously been defined as "academic". "pure", or "basic" research performed in a business setting.

TABLE 1. COMPARATIVE ANALYSIS OF FACTORS USED TO EVALUATE
R&D PROJECT PROPOSALS IN 32 COMPANIES

Factors	Number of Companies
Research and Development	
Likelihood of technical success	15
Development cost	10
Development time	8
Capability of available skills	7
Availability of R&D resources	5
Availability of R&D facilities	3
Manufacturing	
Capability of manufacturing product	12
Facility and equipment requirements	6
Marketing and Distribution	
Size of potential market	23
Capability to market product	15
Market trend and growth	9
Customer acceptance	6
Relationship with existing markets	4
Financial	
Profitability	17
Capital investment required	10
Annual (or unit) cost	7
Rate of return on investment	5
Unit price	4
Payout period	3

Source: (Dean, 1968). Reprinted by permission of the publisher from
Page 49.

Profitability factors are those which allow evaluation in dollars and cents -- i.e., in terms of costs, revenues and profits -- and can be judged collectively in terms of estimated returns on investment. These are the factors ordinarily used in the evaluative formulas devised and utilized by many firms.

Dean cites seven project evaluation formulas in his study. Although each method is different, similar variables are used. A typical formulation is provided by "Olsen's Method" (Kiefer, 1964). This formula allows the computation of an index of value in terms of which alternative project proposals can be compared and judged. These formulas obviously cannot provide the sole basis for choice, because they cannot take account of the above-mentioned intangibles. Nevertheless, they do appear to simplify the decision process somewhat. Briefly stated, Olsen's formula is:

E = relative value of an R&D effort

$$E = \frac{rdpV}{C} = \frac{rdpSPn}{C}$$

V = value of process savings for one year, or 3 percent of the new product sales for five years, or 2 percent of the sales value of improved products for two years

rdp = probability of technical success

C = total estimated cost of R&D effort on project

S = estimated average annual sales volume in units

P = estimated average unit profit

n = number of years.

Project Selection

In practice, project selection differs only slightly from proposal evaluation. The distinction usually derives from the fact that the actual final selection is made by only a few individuals high in the

organizational hierarchy. Two criteria stand out at this point as being the most significant characteristics of most successful R&D projects: low risk and high payout. Those R&D projects that win out in the selection process typically display these characteristics, regardless of any others; and the formula reported by Dean bears this out.

"Formal, quantitative methods for selecting R&D projects are not widely used" (Dean, 1968).^{*} The reasons for their nonuse are varied, but generally stem from the previously noted dichotomy between the rational and nonrational views of innovation. Dean cites additional factors as being:

- "(1) Adequate treatment of risk and uncertainty
- (2) The continuous nature of investments in or expenditures for projects
- (3) The need for multiple criteria
- (4) The interrelationships among projects
- (5) The continuous nature of project selection and review
- (6) The role of experience and intuition in such decision making."^{*}

The following methods have been suggested for use in the project selection process. The calculations and data used in them probably also could be applied to the acquisition of R&D facilities.

(Dean and Sengupta, 1960) -- The value of a project is measured in terms of its net cash flow. The present value of the project is given as

$$V = \sum_{i=0}^n [c_i (1 + r)^{-i}],$$

where

V = present value of the research opportunity

c_i = net cash flow in the i^{th} year

r = expected annual rate of return

i = time index by year

n = total number of years that the income is expected.

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The values of c_i and r must be estimated from past experience and expectations for the future. Projects with the highest V -values would be favored.

(Baker and Pound, 1964) -- Estimates are made of the discounted gross value of a potential project as of the n^{th} period of time prior to achieving technical success. This value includes all revenues or savings from the project, minus all costs of technical development, plant investment, and production (except for R&D costs prior to the achievement of technical success). Data regarding many alternate projects may be considered; and by maximizing the gross value subject to a budget constraint, an optimal allocation of funds can be obtained. However, the data requirements of this method are both numerous and restrictive.

(Minkes and Samuels, 1966) -- This method purports to select an optimal mix of projects, given specific budgetary constraints. Each project is characterized by its cost, its returns (net present value) and the variance of the probability distribution of returns. Mathematical programming techniques are used to solve the mix.

(Harris, 1964) -- This technique is proposed for the selection of new product development projects. From an analysis of company objectives, a complete set of criteria is developed that includes all factors important for successful commercialization and profitability. A simple scoring system is applied in order to obtain a profile of each new product. Selected criteria and a scoring system are shown in Table 2, which is taken from the report.

Investment in Innovation

A separate topic of concern within the literature has dealt with the measurement of investment in innovation by firms. In part, the motivation for this class of efforts has been the observation that there is little conformity in R&D expenditure accounting procedures between firms. Given this obstacle it has been impossible to conduct a large-scale survey of R&D investment. Several studies sponsored by the National Office of R&D Assessment of the National Science Foundation have examined

TABLE 2. CRITERIA USED BY ONE COMPANY IN NEW PRODUCT EVALUATION

Criteria	Score			
	-2	-1	+1	+2
<u>Financial Aspects</u>				
Return on investment (before taxes)	<20%	20% to 25%	25% to 30%	>30%
Estimated annual sales	<\$100,000	\$100,000-\$1 million	\$1 to \$5 million	>5 million
New fixed capital payout time	>5 years	3-5 years	2-3 years	<2 years
Time to reach estimated sales volume	>5 years	3-5 years	1-3 years	<1 year
<u>R&D Aspects</u>				
Research investment payout time	>3 years	2-3 years	1-2 years	<1 year
Development investment payout time	>3 years	2-3 years	1-2 years	<1 year
Research know-how	No experience and no other applications	Partly new, with few other uses	Some experience or new vistas	Considerable experience or potential
<u>Production and Engineering Aspects</u>				
Required corporate size	Any size	Most companies could compete	Average-size or larger companies	Only a very large company
Raw materials	Limited supply of suppliers	Limited available inside company	Readily available from outside company	Readily available from inside
Equipment	New plant needed	Mostly new equipment	Some new equipment	Recent idle plant usable
Process familiarity	New process--no other application	Partly new--few other cases	Familiar process--some other users	Routine process and prominence of other cases
<u>Marketing and Product Aspects</u>				
Similarity to present product lines	Entirely new type	Somewhat different	Only slightly different	Fits perfectly
Effect on present products	Will replace directly	Increase other sales	Slight effect	Increase other sales

Source: (Harris, 1964) as displayed in (Dean, 1968). Reprinted, by permission of the publisher, from pages 76-77.

this issue in recent years. These are:

- (1) Practical Concepts, Inc., The Feasibility of Monitoring Expenditures for Technological Innovation, Vol. 1 and Vol. II, February 1974.
- (2) Denver Research Institute, Surveying Investment in Innovation, February 1974.
- (3) Midwest Research Institute, Investment in Innovation: A Study of Innovation and the Feasibility of Measuring Resources Devoted to It, March 1974.

Each of these efforts examined a small set of firms (usually five) to determine how records were kept on expenditures for innovation and how these could possibly be obtained and analyzed through survey methodologies. These studies agreed that most relevant items of information could be obtained from any particular firm. However, different nomenclature and reporting schemes from one firm to another made it essentially impossible to develop a universal and detailed survey instrument, although an instrument might be designed to obtain comparable data at a very general level.

None of these studies make the distinction between investment in innovation and investment in new research capability. Nevertheless the survey problems that would be encountered in dealing with one of these questions probably would apply to the other as well.

Some other articles that examine relevant budgetary procedures in connection with R&D are:

Sonder, William F., "Pitfalls in R&D Budgeting", Business Horizons, June 1970.

Orton, B. B. and Bradish. "The Treatment and Disclosure of R&D Expenditures", Management Accounting, 51(1), 31-34 (1969).

Impacts

Referring back to our diagrammatic analysis of the literature (Figure 1) it will be recalled that the final broad class of analyses deals with the impacts of the acquisition of new R&D capability both within the firm and outside the firm. Here, consideration must be given both to monetary returns and to business opportunities associated

with the surmounting of technical thresholds. Once again, the absence of detailed case studies in the literature means that no direct answers were found to this aspect of our central problem. However, several studies have been made of industrial innovation that attempt to measure the economic impact of R&D and innovation upon the industry and/or the national economy. Some of the more relevant specific studies of the impact of R&D are summarized below.

(Leonard, 1971) -- Sixteen industry groups were surveyed. It was found that a strong relation exists between research intensity and the rate of growth of sales and assets.

(Fisher and Temin, 1973) -- The "Schumpeter" hypothesis -- that there are increasing returns to scale in R&D -- was tested. The authors did not find the hypothesis to be true; but they did propose a threshold size for firms below which few firms could expect to obtain adequate returns from R&D investments.

(Taymour, 1972) -- Using actual data from Owens-Illinois, Inc., a significant correlation of .66 was found between changes in R&D expenditures and changes in adjusted net sales with a lag of two years. Other findings were:

- "1. There is a strong positive correlation between changes in R&D expenditures and changes in sales with a time lag of two years.
2. An increase of one dollar in the true (deflated) R&D level of expenditure results in an increase of ten dollars in true sales (deflated) two years later. For example, if the R&D expenditure is increased from \$25 million in 1970 to \$26 million in 1971, we can expect the sales of 1973 to be \$10 million more than 1972, plus any other increases that may result from the natural growth of the economy and other business variables.
3. Assuming a 5 percent after tax profit on sales and a life of ten years for the research effect on sales, the marginal rate of return on R&D (after tax) expenditures is probably at least 15 percent and can be as high as 40 percent"

(Mansfield, 1975) -- This study provides both a methodology for obtaining social and private rates of return from investment and analyses of 17 cases to which it was applied. None of the innovations

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specifically involved included new research capabilities. Three categories of innovations were identified as (1) product innovations used by firms, (2) product innovations used by households, (3) process innovations. Separate computational algorithms were used for each category in the calculation of the social rate of return. The primary results of the study were:

- (1) Social rate of return--defined as the consumer's surplus plus net resource savings resulting from the innovation--for these investments was very high (median 56 percent).
- (2) Private returns--defined as producer's net profits resulting from the innovation--were generally lower than social returns (median 25 percent). Six innovations had private return of 10 percent or less while five had 40 percent or more.
- (3) In one-third of the cases the private return was so low that the firm would not have invested if it had had such prior knowledge, but the social rate of return was high enough to have been worthwhile from society's viewpoint.

It could not be determined to what extent there had been rejection of projects with high potential social returns, as only implemented projects were studied. Of particular relevance from this work are the computational methods for measuring the social returns from innovations. These were derived from the theory of the consumer surplus.

(See, 1972) -- Evaluation of R&D using a measure known as the "opportunity criterion" was suggested. This indicator presents a measure of R&D potential in terms of new opportunity. Opportunity is defined as the size of the market for which the product is both technically and economically adequate. This indicator would be directly related to the profits and other aspects of the organization. It is difficult to say whether or not the same indicator could be directly estimated for new R&D facilities.

(Foster, 1971) -- This study utilized a method of calculating the internal rate of return from research to compare returns across industry. The internal rate of return is defined as

$$V = P - I,$$

where P is the present value of the research investment and I is the present value of the research payoff.

There is a possibility that this or a similar device might be modified to provide an estimate of comparative industrial proneness to undertake

new research projects or to acquire new research capabilities.

What Has the Literature Search Told Us?

As a result of the literature search, there are several findings which apply directly to the sense of our questions. Briefly, these can be summarized in the following list:

- Quantitative criteria for business evaluation and selection of proposed R&D projects probably are much less important overall than are qualitative criteria.
- To the extent that private-sector criteria have changed in recent years, they have become more profit-oriented, more closely related to the individual firm's existing markets and products, and much more immediate and short term in their time dimension.
- These business criteria tend mainly to be applied to the whole R&D proposal, not to the proposed acquisition of new R&D facilities.
- To the extent that quantitative criteria are being applied to the acquisition of R&D facilities, it appears that the facilities must pay for themselves in no more than five years, preferably in only one or two years.

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FINDINGS FROM INTERVIEWS WITH SELECTED
KNOWLEDGEABLE PERSONS*

In addition to searching the relevant literature, we have undertaken a series of interviews, both inside and outside Battelle, intended to throw further light on the industrial decision to acquire R&D facilities. The findings from these interviews are consistent with those from the literature search. Although little quantitative information has been collected concerning our central questions, a great deal of highly relevant qualitative information has been collected. Over all, these findings tend to confirm and extend those from the literature. We have deliberately confined this portion of the work to private-sector considerations, involving either industry or Battelle-Columbus. Battelle is a private, not-for-profit, contract research organization.

The Role of Industrial R&D

At the outset, attention is directed to the two different kinds of R&D activity undertaken in the industrial sector: R&D by industry for some level of government (usually the Federal Government); and R&D by industry on its own account. Only a small part of the latter is extramural -- when industry carries out R&D for itself, it does so almost entirely in-house.

When examining the justifications for undertaking R&D or for acquiring particular R&D facilities, the question of sponsorship becomes crucial. If the R&D is being performed for the government, that in itself usually is sufficient to justify outlays on facility. If the particular facility being acquired cannot be entirely funded by research contracts in hand, it must be justified by the likelihood that additional contracts will be forthcoming. If, on the other hand, the facility is desired solely for intramural projects, the expenditure must be justified by the justification of the projects themselves.

* These interviews were undertaken and an early draft of this section written by Dr. Herbert S. Kleiman, a senior researcher in Battelle's Economics and Management Systems Section.

The non-Battelle industrial experts interviewed during this study generally held the opinion that expenditures on R&D plant and equipment constituted a relatively small proportion of total R&D costs. This derives from the fact that identifiable R&D facilities are associated more with research than with development. Generally speaking, the research costs of an innovation are relatively small when compared to the costs associated with development, production or marketing.

The Contributions of Industrial R&D

Industrial activity is generally undertaken to accomplish one of three ends: to make a profit, to protect or expand a profitable market, or to penetrate a new (and presumably profitable) market. The R&D activity contributes in two basic ways: it may improve the existing product line, or it may lead to a new product line. Most industrial R&D activity is directed to the more mundane and less glamorous evolutionary improvements. The significant new innovations -- such as a xerographic copier or a mini-computer -- are infrequent. More common, although still relatively few in number, are the products that are new to the company, but not to the society -- e.g., General Electric's diversification into computers and jet turbines or the Rohr Corporation's move into ground transportation vehicles. We can say that the contributions of R&D can be grouped into two general categories: (1) improvements in kind, i.e., new capabilities not previously available either to the company or to society; or (2) improvements in degree, i.e., incremental changes in the directions of lower costs, faster turnaround, better performance, and the like.

Innovations in Industrial R&D

These same two categories also describe the types of R&D facilities with which industry must work in carrying out its product-improvement projects. Admittedly, the differentiation between these two groups of R&D facilities may sometimes be vague or even arbitrary. Often, for example, the improvements in degree are of such a magnitude that, in practical terms, there were no realistic predecessors.

Improvements in Kind. Just as there are relatively few product breakthroughs, such as xerography, there are relatively few cases in which new R&D equipment confer significantly higher capabilities for industrial research. Some few of these have appeared on the scene. Unfortunately, however, the interviewees could give no specific instances of the justifications used by corporate Research Directors in acquiring them. Examples of these breakthrough facilities are:

- The electron microscope offered a major improvement over the optical microscope in terms of both magnification and resolution. Its resolution of a few Angstrom units is about three orders of magnitude (approximately 1,000-1,500 x) better than that of the optical microscope. Specimens such as viruses can be seen with the electron microscope that could not be viewed previously. The electron microscope first appeared in the late 1930's, and now is a common laboratory tool. Its price ranges from \$20,000 to \$200,000.
- A development from the electron microscope, the scanning electron microscope (SEM), although providing resolution of only some 100 Angstrom units, allows a researcher to view a surface in three-dimensional detail. The three-dimensional capability provides a unique understanding of surfaces, using a principle that is somewhat different from that of the electron microscope. The prices of the SEM approximate those of the electron microscope. Often the two instruments are used together, since neither can totally duplicate the other. The SEM has proved to be especially useful in electronics and metallurgy.
- The laser is now used as a standard tool for Raman spectroscopy, a laboratory technique for measuring temperatures in hostile environments without in any way disturbing them. This type of measurement requires an intense, focused, monochromatic light source which the laser provides. With it, temperatures in boilers or at the exits of jet turbines can be measured remotely. Previously, measurement techniques required intrusions that altered the parameters being investigated. Depending on their size, type, and power, industrial lasers range in price from \$20,000 to more than \$100,000.
- Computers allow for a totally new dimension in laboratory investigation, especially when real time analysis is required or desirable, as with chromatography and spectroscopy. With the computer, various parameters can be measured and subsequently analyzed. The ramifications have been numerous. In addition, the computer has facilitated design and development (e.g., in the aerospace industries) by allowing for

simulation not previously feasible. Depending on their sizes and capabilities, the range of computer costs is quite wide, going from under \$1,000 to over \$100,000.

Improvements in Degree. Just as the vast bulk of R&D activities lead to evolutionary and incremental improvements in the product lines, a large proportion of the improvements in R&D capabilities that result from new technical equipment are also incremental. Typically, the function could have been (and perhaps was) performed previously, but it probably was more costly, more time consuming, or less effective in a performance sense. Some examples of this situation follow:

- In addition to the applications mentioned in the context of differences in kind, there are many other computer applications which allow various calculations or other functions to be performed routinely whereas, under earlier circumstances, they were performed only periodically, selectively, less effectively, and at greater unit cost. In this aspect of their usage, computers of many types have been integrated into research laboratory operations. Their contribution must be judged both in terms of their specific contribution to the given function and in terms of their general contribution to improved efficiency.
- Improvements in spectrometers have allowed researchers to better analyze materials and understand their structural and dynamic characteristics. With cost ranging from about \$15,000 to at least \$250,000, various spectrometers can be teamed with computers and other laboratory equipment to fulfill a variety of analytic or quality control functions with great efficiency. Except for a very few limited instances, none performs functions that cannot be achieved in some other, but probably more costly manner.
- The chromatograph achieves a much improved separation of complex materials into their component parts. At capital costs usually below \$10,000, it yields much higher purity levels of the several components and can utilize much smaller samples. Prior techniques to achieve this same separation -- e.g., fractional distillation -- are much more difficult and time consuming.

Facility Justifications in Industry

The criteria which must be met in order to justify proposed R&D projects are much more stringent in industry today than they were only a

few years ago. There is generally a greater insistence on the part of corporate managements that research projects must make clear positive contributions to the achievement of corporate goals. While there have been recent changes in the kinds of goals entertained by corporate executives -- e.g., a greater formal recognition of "social accountability" -- these criteria are primarily hard-nosed and businesslike.

It must be emphasized at the outset that all the criteria to which industry R&D is subjected are essentially expectational in character. The very nature of R&D activity dictates that expenditures usually must be made over a relatively long period of time in order to achieve a projected future payoff. The nature of that future situation must be acceptable to both the viewpoint and the value-structure of management before any possibility of a justification can materialize.

Probably the most persuasive argument that can be used to justify any specific research program or the purchase of any expensive piece of equipment is the demonstration that the company cannot compete or cannot compete as well in a given market without it. This demonstration often may be made in qualitative, perhaps even visceral terms. Nevertheless it is usually effective. This line of reasoning suggests that any argument that cannot be coupled to the company's present product line -- such as the statement that it will enhance the understanding of a given scientific area -- is seldom potent or even credible.

Providing a new capability per se is not a generally persuasive argument unless it can be coupled to a specific business need. Understanding for the sake of understanding is inadequate. This further suggests that any such acquisition must first be sold on its own merits before it can be justified in terms of its ability to advance the company.

Since relatively few new research facilities offer a "breakthrough" capability, most such purchases must be justified in terms of improved productivity and based on a good understanding of the existing research situation. Typically, the argument to acquire a new capability must be based on qualitative rather than quantitative criteria, since we have shown that it is extremely difficult to justify it quantitatively. The research activity demands only a small share of total R&D costs. For this reason such acquisitions ordinarily must be justified in terms of faster turnaround, shortening of

investment periods, or reductions of risks. Five years seems to be regarded as too long to wait -- even for a big success -- in the eyes of most business decision makers.

In summary, we can say that with respect to the criteria it applies to the justification of proposed R&D activities or capabilities, corporate management has a very short time horizon and thinks strongly along the lines of the firm's overall purposes. Despite the high degree of pragmatism implied by this statement, management still applies many qualitative criteria. Generally, however, the R&D function (like most others) must meet the ultimate criteria of improved productivity, lowered costs, and substitutions of capital for labor, all within the familiar product mix. Often a new project or facility can be justified in terms of its defensive value in habitual markets; more occasionally it may be justified by the promise of a preemptive move into a new market.

The Battelle-Columbus Experience

As a contract research institution, Battelle's Columbus Laboratories often must add to its research capabilities for one or more of a variety of reasons. In the first place, it must be able to attack wide-ranging problems brought to it by industrial or governmental sponsors. In the second place, it often needs new facilities in order to discharge social obligations associated with its charter as a charitable trust. Finally, it may acquire new capabilities for the purpose of attracting and/or holding the staff needed to carry out those first two functions.

During 1974-75, Battelle Memorial Institute achieved final settlement of certain long-standing legal actions that involved the United States Internal Revenue Service and the Attorney General of the State of Ohio. Among the consequences of these two settlements, a significant reduction occurred in the financial resources freely available to the Columbus Laboratories for use in acquiring or expanding its R&D capabilities. Three recent BCL experiences in acquiring R&D plant and equipment are discussed below. All three were begun before the settlements and two have continued since then. Before the settlements Battelle had a capital portfolio that generally exceeded year-to-year requirements. For this reason, pre-settlement criteria for large R&D plant-and-equipment decisions generally were not stringent. The settlements

greatly reduced the funds available for new capital formation, thereby forcing the adoption of much more businesslike criteria in this respect. In the discussions which follow, no attempt has been made to trace the impacts of the settlements upon the three cases.

Animal Facility

A customized animal facility costing about \$6 million is under construction to house a wide variety of laboratory animals for various experiments. The facility can accommodate numerous cage configurations for many different types of animals, and it provides a wide range of special instruments and laboratory facilities to support many kinds of experiments. The bulk of the funding of this facility comes from general Battelle Institute funds, so that justification at the laboratory level has not been in terms of specific business criteria.

In view of Battelle's status as a charitable trust, much of the justification for this facility undoubtedly was in terms of its potential contribution to the public good, especially in biological fields related to cancer and the testing of drugs and chemicals. Nevertheless, there was a high potential for research contracts implicit in the decision. Prior to the time of this decision, the Battelle life sciences area had not performed up to expectations. The decision to create the new facility was made within the context of a larger decision which also involved the appointment of a new department head and the development of a new program designed both to establish a reputation in the life sciences and to achieve a higher volume of outside funding. It was argued that this investment would attract programs totalling \$10-15 million over a 10-year period. This implies an expectation of about two dollars for each capital dollar spent. At the time the decision was made to move ahead, no such contracts were in hand to justify those expenses, although the outlook appeared positive. The facility is not yet fully completed, but it already appears that those expectations probably were quite conservative and that the facility will more than justify itself by that criterion.

Clean Room Facility

A "clean room" is typically associated with the demanding needs of selected space and military developments and/or fabrications. The clean room environment minimizes the possibility that any contaminants, such as dust, may somehow enter particularly sensitive fabrication processes, thereby compromising or even totally disabling a critical component. Such facilities have been most closely associated with the fabrication of highly sophisticated electronic components. In the late 1960's, a Battelle decision was reached to build an enlarged clean room facility*.

The larger clean room, which cost in the neighborhood of \$100,000, was justified in the following terms:

- (1) The clean room was needed in order that Battelle might compete more effectively in programs in this general area of activity
- (2) The facility would enhance Battelle's capability on related programs, either in hand or anticipated
- (3) Although the level of "cleanliness" would not approximate that required for the semiconductor facilities of a private manufacturer, it would add greatly to Battelle's competence in this general area of work.

The cost of the new facility involved primarily building modifications (since most of the equipment could be transferred from the existing facility). For this reason it could be financed from Battelle Institute capital accounts, a source which then did not have stringent criteria for justification. We find no particular quantitative arguments that were made to justify the acquisition. The main argument simply was that Battelle needed to improve this strategic capability.

Changes occurred in the research market that were directly or indirectly attributable to declining Federal funding of military/space R&D during the late 1960's and early 1970's. One direct result of this decline was a reduction in demand for the kinds of research that would need, support, and justify the enlarged clean room. In other words, the expectations leading to that particular investment were never realized.

* The existing clean room had cost about \$20,000 and had been built using general overhead funds, rather than departmental funding.

Laser Facility

Beginning in 1970, the decision was reached to invest in a large laser facility. This investment, unlike the two previously discussed, was primarily in equipment, with only minor modifications required in physical plant. The original decision -- involving the purchase of a \$280,000 laser -- proved to be the first in a very complex set of decisions into which a variety of changing factors and justifications have entered. Some of these shifts are indicated by the following highlights:

At the time of the original decision, it was contended that Battelle would become one of only two or three research firms with lasers of this size. Given the supplemental services and applications that Battelle could offer, the total facility would be unique and was expected to lead to new program revenues totalling over \$400,000 per year in about five years. Accumulated sales during this period were expected to approximate \$1 million. This would imply a five-year return of \$3-4 of contracts for every capital dollar.

The Battelle Institute (BI) was expected to fund between \$50,000 and \$90,000 per year of fundamental research in fusion technology, simulations, and related fields; and the firm from which the equipment was purchased agreed to purchase \$55,000 per year of laser time. Since the equipment could be depreciated on a straight-line basis with a 5-year life, capital costs would be on the order of \$55,000 per year and would be more than covered. The remainder of the revenues would support the associated staff.

Since 1972, this laser has been enlarged, under Battelle Institute encouragement, at a total cost of about \$1.5 million. It is now quite possibly one of the most powerful such instruments in the world. A research program in laser fusion has been funded by BI for about \$1 million. The justifications for these later developments have been primarily in terms of two things: the broad Battelle obligation to contribute to the good of mankind, and Battelle's growing identification with all aspects of energy technology and research. At the original level of expectation, this investment would need for justification a total flow of contracts between \$4.5 million and \$6 million. A large part of this quantitative performance criteria implicitly has been replaced by the hope of social contributions.

Summary

On reviewing this very limited set of Battelle investments in new R&D capabilities, several generalizations emerge. In the first place, a major justification for the various expenditures seems to lie in Battelle's need or desire to compete better in building up its programs in current or new research fields. Implicitly it seems to be argued that without such enhanced capabilities, Battelle's chances of obtaining or expanding these new programs would be reduced. In the second place, these arguments seem to have been made qualitatively, rather than quantitatively. In the third place, many of these arguments have been couched in terms of Battelle's obligations to contribute to the general benefit of society.

It should also be noted that, largely because Battelle is a not-for-profit organization by virtue of its charter, many of the justifications which seem to have been persuasive would not be equally effective with the management of a typical profit-making business enterprise. While competitive effectiveness in the R&D market is a major justification -- and it is a justification that, at least in the nominal sense, could be made in an industrial situation -- its full significance in the Battelle context is more "governmental" than it is "industrial".

Finally, attention must be called to the very special capital abundance that characterized Battelle's pre-settlement situation. Unlike most industrial enterprises, in which R&D programs must always compete for scarce capital resources with production and product marketing, R&D is Battelle's product. Furthermore, in recent pre-settlement years, there was plenty of capital to go around; so that strict applications of stringent criteria were unnecessary. In post-settlement Battelle, however, capital has become so scarce relative to investment opportunities that potential payoffs must be balanced carefully. In this regard, even though we were unable to obtain any specific quantitative information to support it, we can infer that Battelle is becoming more like private business in the criteria it applies to acquisitions of new R&D capital.

What Have the Personal Interviews Told Us?

We have examined some specific cases drawn from Battelle's own experiences, primarily because they throw some light on the criteria that are applied to acquisitions of R&D facility. Battelle is not a profit-making business, therefore we can be certain that industry generally would be much stricter than Battelle in comparable decision criteria.

Taking the two cases for which some quantification is possible, we find that the following criteria were applied:

- Animal facility -- a sales-to-investment ratio of 2:1 over a 10-year period
- Laser facility -- an early sales-to-investment ratio of 3:1 or 4:1 over a 5-year period

If we reduce these two cases to comparable time periods, we can say that the range of sales-to-investment over a 5-year period would have been somewhere between 1:1 and 4:1. Assuming that Battelle has become significantly more demanding as a result of the settlements and that profit-making private industry is certain to be even stricter in criteria than Battelle, we can begin to get some idea of the criteria that business applies to acquisitions of R&D facilities. Intuitively, 10:1 over 5 years would not be impossible; and that would probably require that the facility at least repay its full cost during the first year of use.

Turning now to the nonquantitative criteria applied by business, we find that:

- The R&D facility must contribute to the firm's existing line of business
- The most telling business argument for acquiring a facility is defensive -- without it the firm cannot compete or will compete less effectively in its current markets
- Regardless of anything else, it must be demonstrated to the business management that the new R&D facility will lead to lower costs, higher productivity, better profits -- not that it will provide new knowledge
- There is a place for public service as a justification for the acquisition of R&D facility. However, in industry generally, it will rank far below contribution to profits in terms of priorities.

SOME FURTHER GENERALIZATIONS CONCERNING
THE INDUSTRIAL R&D DECISION

In this section, we wish to address briefly the central question within the context of our findings. We do this in search of guidance concerning the following matters:

- What is the place of industrial R&D within the total R&D picture?
- What factors and considerations dominate the R&D decision by industry as to which R&D projects to undertake on its own account and what facilities to acquire and use?
- What factors and considerations affect the industry decision concerning R&D for the benefit of society?
- From a nonquantitative point of view, what are the primary relationships between industrial R&D and national growth?

The remainder of the section treats these four questions in that order. It builds in considerable part (but not completely) upon our findings.*

The Place of Industry in R&D

If we take the measures of R&D funding/performance by the National Science Foundation at their face value, we can draw certain generalizations concerning the significance of industry in the totality of U.S. R&D. Industrial funds support about 43-44 percent of all R&D activity, and industry performs almost all the work that it funds. This industrially funded and performed 43 percent (\$14.7 billion out of \$34.3 billion in 1975) is controlled entirely by the decisions of corporate management.

In 1975, the Federal Government funded another \$9.2 billion of industrial R&D performance, raising industry's share of total performance to 70 percent. The approximately 27 percent of all R&D that is

* In order to place the findings concerning industrial R&D criteria within a frame of reference that embraces total U.S. R&D activity, we have drawn on the publications of the National Science Foundation's "Surveys of Science Resources". See especially: National Patterns of R&D Resources: Funds and Manpower in the United States, 1953-1975 (NSF 75-307, April 1975); and Research and Development in Industry, 1973 (NSF 75-315, May 1975).

Federally funded and industrially performed is only partly controlled by corporate management. The ultimate selection of these R&D projects is determined generally by the sponsoring Federal agencies.

In a typical year, of the total R&D performed by industry, regardless of the funding, less than 3 percent was classed as basic research, less than 18 percent as applied research, and 79 percent as development. Viewed in another way, industry ordinarily performs about 16 percent of all U.S. basic research, about 55 percent of all applied research, and about 84 percent of all development.

Considerations Affecting the Industry R&D Decision

As we have already seen, the main criteria by which industry selects R&D projects on its own account relate to their ultimate contribution to survival and profits. The projects most likely to be undertaken will be those promising to make an immediate contribution to existing product lines by protecting or expanding their market shares, or by reducing their costs of production. To the degree that management must wait for a payoff or must produce and market unfamiliar new products, the associated R&D work rapidly loses its place in the funding queue.

Similar considerations affect the decision to acquire new R&D capabilities. Those will be favored which are generally applicable to the improvement and strengthening of on-going product lines or R&D projects or which promise to reduce the costs of work that must be done. Facilities that are requested because they promise to open up exotic new fields of research generally end up with low probabilities of being acquired.

Considerations that Affect the R&D Decision by Industry for Government

To the extent that industrial R&D activity is funded by the Government, or to the much smaller extent that, while industrially funded, the R&D projects are being undertaken for the public good, this very fact increases the likelihood that associated facilities will be acquired. This becomes

especially true in the cases of organizations (like Battelle) for which R&D is the output. Industry, in other words, will be much more likely to acquire or support an exotic facility that must be used for Federally funded R&D projects than it would be use it for industrial projects. Similarly, to the extent that the firm feels compelled to make research-related contributions to the good of mankind ("the public interest") the affected R&D projects are insulated from the usual business criteria for selection and justification.

The Relationships Between Industrial R&D and National Growth

At this point, having summarized the generalizations that can be made and/or supported by our study's findings, it seems desirable to turn our attention to the larger set of considerations to which this study ultimately must contribute. Any direct or indirect support that NASA can provide for industrial R&D probably will be justified, in the final analysis, by the extent to which that industrial R&D contributes to national economic growth.

Almost everyone who studies the relationships between technology, on the one hand, and economic growth, on the other, feels that the former contributes to the latter in many ways. There is the danger, however, that a naive linking of these two phenomena may lead to the feeling that there is a certain direct and totally desirable one-to-one relation -- that every industrial R&D activity is inevitably justified by its contribution to national economic growth. This is far from the case.

In order to clarify some of these relationships, we need to bring together several generalizations. Although by no means profound, some of these points often are overlooked. They need to be reemphasized from time to time.

Sources of New Technology

If we define technology as the totality of our ways of productively controlling the natural environment, we are often tempted into such simplistic generalizations as "technology leads to economic growth, R&D leads to technology, therefore all R&D leads to economic growth".

What may be overlooked, however, is that technology arises in many times and places, and not always results from the particular R&D under consideration. Without exhausting the possibilities we can say that new technologies may result from:

- (1) R&D performed in the distant past
- (2) R&D performed abroad
- (3) R&D performed in another industry or firm and accessed by license
- (4) Own recent R&D
- (5) Industrial or personal experiences that cannot conceivably be classified as R&D

Our only reason for elaborating this point is to emphasize the fact that the best source of new technology is not necessarily the current funding of additional R&D activities. Moreover, if we find that a certain level of R&D expenditure has been made, this need not imply that a certain level of successful new products or new processes will flow from it automatically.

Sources of Economic Growth

When we turn to the problems of growth, our causal generalizations are totally dependent on our definitions. If we assume that growth can be measured in terms of hedonistically defined "utility", anything that increases pleasure and reduces pain (e.g., mass hypnosis) would contribute to national growth. In our current definitions of Gross National Product (GNP) we measure the outputs of many service industries (e.g., education) in terms of what we pay the suppliers of those services (e.g., teachers). This means that anything that increases the teachers' pay increases the output of education and contributes to economic growth!

If we assume for the moment that any economic good or service can be quantified meaningfully and measured, and if we further assume that all these separate measures can be summed to a meaningful total, we can discuss the causes of economic growth in terms of the factors that are capable of altering that total: The total output of goods and service would be a function of the availability and use of productive resources. These resources would be made up of capital (plant and equipment), energy and material resources, productive labor, technological know-how, and

management expertise. Leaving out considerations of the business cycle, we can say that economic growth occurs any time the total output is increased by increasing the totality of employed resources. Let us examine the several processes that may contribute to this growth.

The process of increasing the total capacity of plant and equipment is termed investment. Net investment can come about because we create more capacity of the existing kinds, or because we design new forms of capital that can do more or different things. This latter could be the result of R&D or of any other of the above-listed sources of technology.

Increases in available natural resources can come about because we discover new physical reserves; or because we discover (through R&D, etc.) more efficient methods for recovering known reserves; or because previously known, plentiful, but relatively useless natural resources can be utilized by new productive methods (also R&D). Increases in productive labor can come about either through population growth or through education (i.e., increasing individual levels of knowledge and/or skill). Increases in technological know-how and management expertise can come about through education, through serendipity, and/or through R&D.

Obviously, there are several factors that are capable of leading to economic growth; and R&D is one of the more important of them. This does not mean, however, that all R&D inevitably leads to growth. For instance, if R&D leads to the discovery of new, more effective ways of production, but does so only by diverting so many resources from other uses that labor quality, capital, and access to raw materials are reduced -- economic decline might occur rather than economic growth.

Offsets to Growth

There are two major ways in which the growth-inducing impacts of R&D may be offset: (1) by actual depletions of one or more crucial resource categories or (2) by diversions of those resources into nonproductive uses. An example of the first would be the using up of fossil fuel reserves at a faster rate than they could be discovered or than new energy technologies could be developed. An example of the second would be the diversion of capital formation capacities from productive equipment into pollution abatement

equipment. Even if that diversion were necessary for the continued survival of the race, it could still lead to negative growth.

Some Final Conclusions

Given that R&D activities may generally associate with national growth, there are many pitfalls that can trap the uncritical application of these generalizations. In any short-run situation there are many so-called "side-effects" or "externalities" of otherwise attractive new technologies that more than offset their apparent contributions. Thus a more correct generalization would be that there are technologies that make net contributions to growth, but not all technologies do so. It must be emphasized in this connection that the so-called "market test" cannot be applied here. Many technologies which are extremely profitable for short-term use by a single firm or industry may prove socially disastrous in the longer run.

Looking at the relationship between R&D and socially desirable technology, we must also keep several other generalizations in mind. First, the business criteria for use in selecting R&D projects or facilities carry no automatic implication of social benefit. Second, regardless of its attractiveness otherwise, the most productive R&D project is always the one that discovers and puts into place the last piece of the particular technological jigsaw puzzle. And third, the time lags between R&D effort and technological payoffs may span days, years, decades, or centuries.

In the long-term there is a positive set of relationships among R&D, technological change, and national economic growth -- but these relationships are extremely complex. The fact that a particular project or facility meets current business criteria for selection does not mean that it represents the socially most desirable use of our scarce resources; and inversely, the fact that a particular project is socially desirable does not assure that it will meet the selection criteria of business and be undertaken.

ANALYSIS OF THE EFFECTIVENESS OF INDUSTRIAL R&D

PART II:

STATE-OF-THE-ART REVIEW ASSESSING
THE ROLE OF R&D IN ECONOMIC GROWTH

by

W. Halder Fisher and John L. Moore

INTRODUCTION

This is the Part II report of a task involving analysis of the effectiveness of industrial R&D conducted under Contract NASw-2800, "NASA Applications Studies -- New Initiatives". The task takes the form of a two-part effort: Part I involving the definition of the problem and an attempt to examine it in preliminary terms through the use of secondary data; and Part II addressed to a more complete, perhaps primary, analysis.

In spite of a variety of studies, the quantitative role of R&D in economic growth is not well understood. In part, this stems from theoretical uncertainty concerning the causal relationships into which R&D activities may enter. Another difficulty derives from the lack of adequate data to support detailed studies of how past R&D projects have in fact affected productivity and economic growth. These problems underscore the need for exercising great care in evaluating the potential economic returns to any specific set of R&D activities or expenditures.

Because public R&D is often justified on the basis of its asserted benefits, it is important to understand the various methods employed in measuring the interrelated roles of R&D, technical (technological) change, and economic growth. This discussion is intended to provide an overview of major approaches and findings concerning the roles of technical change and R&D in United States economic growth. The initial purpose of this overview is to identify the conceptual and practical issues inherent in any quantitative analysis of the contribution of R&D to economic growth. Its ultimate intent, however, is to assist NASA in developing approaches for analyzing the economic implication of its own R&D efforts.

We have undertaken in this discussion to weave together three major themes: a review of concepts and issues, an examination of general

alternative approaches and findings, and an evaluation and comparison of these approaches in terms of their applicability to NASA programs.

CONCEPTS AND ISSUES

Recent empirical attempts at measuring the relative contributions of various factors to economic growth all fall within a broad framework of traditional economic growth theory. A brief critical review of these concepts, the perceived role of technical change in economic growth, and the general problems inherent in economic growth analysis are necessary background to a review of alternate quantitative approaches.

Analytical Framework

Economic growth is traditionally defined as an increase in the total real output of goods and services, usually expressed in per capita terms. The traditional measure of economic growth is per capita gross national product (or, alternatively, national income) adjusted for inflation.* Gross national product is defined as the annual dollar value in current prices of all goods and services produced for sale, plus the estimated value of certain imputed outputs. National income, on the other hand, is defined as the total compensation of the elements used in production which comes from the current production of goods and services by the national economy. It consists of wages, interest, rent, profits, and the net incomes of the self-employed. The difference between national income and gross national product is accounted for by capital consumption allowance (depreciation)

* To arrive at an approximation of the actual real annual output of goods and services produced by an economy, it is necessary to adjust annual money value of gross national product (or of national income) for increases attributable to inflation or general price level increases. For example, given that the money value of GNP rose by 6% for a given year, no real growth would occur if the increase was due to a 6% rise in the overall price level. Price indices such as the GNP deflator are used to adjust annual values of GNP for inflation.

and by indirect business tax and nontax payments (Federal excise taxes, customs duties, state taxes and fees, and local property taxes). While the output of an economy may grow from year to year, if population is growing at a faster rate, per capita output will be declining. This is often the case in some developing nations; but it has occurred only on an infrequent, cyclical basis in the industrialized nations.

Although a variety of specialized theoretical approaches are used to analyze the factors contributing to economic growth, growth analysis proceeds from a general framework described by the functional relationship $Q = f(K, L, N, T)$, where Q is the quantity of output; K represents capital inputs; L is labor inputs; N represents natural resources or materials; and T represents the role of technology. In this formulation output (Q) is inflation-adjusted GNP or national income. Capital (K) is the mix of machinery, buildings, public infrastructure, tools, and other equipment used in the process of production. Capital is usually measured by its asset value, adjusted for age and other significant characteristics. Labor consists of the spectrum of human services, including all forms of unskilled, semiskilled and skilled work, as well as the managerial, intellectual, and technical inputs of professionals and managers. Natural resources include both renewable and nonrenewable inputs, as well as land or space itself. Renewable resources include forests, soil fertility, products from crops, fisheries, etc. Nonrenewable resources include especially metals, minerals, and fossil fuel energy. The direct role and contribution of natural resources is usually ignored in analyses of economic growth, on the assumption that technology always has and will continue to offset exhaustion or diminishing returns. Although technology (T) can be defined in a variety of ways, its broadest meaning encompasses the accumulation and application of knowledge to the productive process. Technology is considered to be scientific, engineering and managerial knowledge which makes possible the conception, design, development, production, and distribution of goods and services.

The interaction of pervasive changes in the characteristics and combinations of capital, labor, natural resources, and technology have allowed more or less continual growth in per capita output of the U.S.

What the important factors are that contribute to economic growth and how R&D affect these factors has been the subject of considerable theoretical debate and of a variety of empirical studies. Factors that are often cited include:

- Growth in the labor force and change in its composition
- Growth in the stock of capital
- Economies of scale (i.e., a doubling of inputs resulting in more than a doubling of outputs)
- Better social (political) organization and management techniques in resource allocation
- Increasing breadth and depth of education resulting in a more effective work force
- More "efficient" capital stock
- New discoveries of natural resources.

General Role of Technical Change in Economic Growth

Technological change in economic growth has allowed more or less continual expansion of traditionally measured output offsetting diminishing returns experienced in natural resource and energy inputs necessary for the operation of the economy. Technical change can be defined in a variety of ways, but generally it is defined as an advancement in the state of the art or knowledge of production that leads to a fall in the real cost of production or that introduces new products which both expand the range of possible activities and reduce the costs. The general tendencies of technical change in the last century in the industrial nations have been increasingly to substitute capital and fossil fuel energy for human labor, to develop substitute materials, and to extend man's communication and computation abilities through the development and refinement of electromechanical and electronic devices.

While the definition of technical change implies a tangible process, advances in knowledge per se defy meaningful quantification. As a result we have many attempts to measure technical change by its effects. This is

accomplished by using as a measure the effect on the growth of factor productivity that is not accounted for by other inputs; in other words, by leaving the contribution of technical change as a residual.* This is to say that all growth in output which cannot be attributed to increases in the quantity or quality characteristics of labor or capital** are attributed to advances in the state of knowledge or technical change. As Kennedy and Thirlwall point out, this approach has the distinct disadvantage of not being able to separate technical change from any unspecified other inputs, thus possibly confusing advances in knowledge with other factors which may raise productivity.* The authors conclude that there may be no alternative to this approach and the best for which we can hope is a sensible interpretation of the residual.*

Channels of Technical Change. Changes in the state of the art of production may lead to greater productivity through a number of mechanisms. These include improvements in the state of the art which increase the effectiveness and ultimately lower the relative costs of capital equipment. Such improvements allow an increased flow of output from the same value inflow of resources. Conversely, advances in the state of the art may allow the same flow of output from a reduced value inflow. Advances in knowledge and the state of the art may also increase productivity through improved processes or production techniques that lower unit costs of production. Finally, technical change may result in new products or materials that serve as substitutes for natural products or which expand the choices available.

While generic classes of technical change can be defined, the process of increasing productivity is a blur of forces and phenomena, some few of which can be isolated, but most of which can only be observed in combination with other equally pervasive influences.

* Kennedy, C., and A.P. Thirlwall, "Technical Progress: A Survey", The Economic Journal, 82 (325), 13 (March, 1972).

** Confining the concept of "factors of production" to land, labor, and capital is coming increasingly under severe theoretical criticism. We will discuss this point later.

Role of R&D in Technical Change. The link between R&D, technical change, and economic growth is neither well understood nor easily analyzed with any degree of rigorous precision. Research and development may lead to the development and diffusion of new technologies, but it is extremely difficult in advance to quantify project outcomes. In classifying R&D, the traditional approach is to divide the activities between basic research, applied research, and development. The standard definitions of these categories, as given by the National Science Foundation, follow. Basic research involves original investigations that are undertaken for the advancement of scientific knowledge, but do not have specific market objectives. Applied research involves investigations that are directed toward the discovery of new scientific knowledge and that have specific commercial objectives with respect to products or processes. Development includes technical activities of a nonroutine nature that are directly concerned with translating research findings and/or other scientific knowledge into new or improved products or processes. It is in this last phase, development, and in diffusion that technical change has its greatest direct effect on economic growth. But thorough analyses of the contributions of advances in scientific and engineering knowledge which may have preceded development and diffusion are also required if the process is to be understood. The identification of advances in the state of the art which do not originate in organized R&D is also an important element of any analysis of the specific role of organized R&D.

Thurow provides an alternative tripartite classification focused on the budgetary process. This categorization includes basic-capabilities R&D, mission-oriented R&D, and occasional highly focused, all out, massive mobilization R&D, represented by the Manhattan or Apollo projects.* Basic-capabilities R&D is designed both to build up a general fund of knowledge from which mission-oriented R&D and massive mobilization R&D can flow and

* Thurow, Lester C., "The Relationship Between Defense-Related and Civilian-Oriented R&D Priorities", Prepared for the Subcommittee on Priorities and Economy in Government of the Joint Economic Committee, and the Library of Congress (April 23, 1976).

to maintain a level of capabilities that will allow the country to rapidly take advantage of scientific breakthroughs wherever they may occur and whoever may make them. Mission-oriented R&D is more focused in that it is generally possible to state where benefits are to be expected and the breakthroughs that would be necessary to achieve the desired benefits. Massive mobilization R&D would be undertaken whenever the mission is highly defined, when all the basic scientific knowledge needed to support a massive effort is known to exist, and where the benefits are perceived as so large that the nation would be willing to devote a significant fraction of its resources to achieving these specific objectives. Thurow's classification has distinct appeal within the context of this analysis, since it would allow quite precise classification of the initial nature and purpose of each specific NASA R&D project.

Shortcomings of Measurements of Technological Change. In reviewing methods for directly measuring the contribution of technical change (and indirectly the contribution of R&D) to economic growth, several important conceptual issues should be kept in mind.

Foremost among these issues are the problems inherent in using GNP or national income as a key variable for measuring the contribution of technical progress. As Nadiri and others have stated, both these variables exclude nonmarket activities* and understate the importance of new products as a vehicle of technical change.** More importantly, the present definition of GNP treats expenditures on pollution abatement as an addition to GNP, rather than deducting such expenditures as a cost of certain types of technological advances. This double counting, therefore, overstates the

* Nonmarket activities include such things as the economic services of housewives or the do-it-yourself improvements that home owners make in their dwellings. Nonmarket activities should be included as part of gross national product, but are excluded because no payment is made for the services rendered.

** Nadiri, M. Ishaq, "Some Approaches to the Theory and Measurement of Total Factor Productivity: A Survey", Journal of Economic Literature VIII (4), (December, 1970).

contribution of some forms of economic growth. In view of the significant welfare implications of technological side effects, this is an important problem.

Another important inconsistency in the treatment of the national accounts is the classification of education costs as expenditures rather than as investments in society's stock of knowledge.

Of increasing importance in the literature relative to these measurements of economic change, many economists are raising questions concerning the concepts of "factors of production" in terms of which growth is explained. Traditionally, these factors of production are defined as embracing land, labor, and capital. Recently, for example, Boulding has criticized this trilogy as being related to distribution of income, but not to production of goods and services.* Instead, he names as the factors of production "know-how, energy, and materials". Georgescu-Roegen has made essentially the same point.** Boulding goes on to imply that this fallacious (but traditional) conception is one of the main elements that keeps economics from becoming truly scientific.

Finally, it is absurd to view all technical change as being good per se. Individually and socially, the human capacity to accept rapid and continual change is not infinite. It is therefore increasingly important that we assess the long-range economic and social cost of specific contemplated technical advances. Recent controversies over the SST and the continuing controversy over nuclear power provide good examples of the increasing attention that technological issues are receiving. The applicability of any specific methods for analyzing the economic implications of NASA's R&D activities must be viewed against such considerations as these.

* Boulding, Kenneth E., "Economics for Good or Evil", Technology Review 5 (July/August, 1976).

** See, e.g., Nicholas Georgescu-Roegen, "A Different Economic Perspective", Prepared for presentation at the February, 1976, Annual Meeting of the American Association for the Advancement of Science.

ALTERNATIVE APPROACHES TO THE MEASUREMENT OF TECHNICAL CHANGE

A large number of empirical studies have been conducted concerning the determinants of economic growth. Only a few, however, have attempted to quantify the relationships between R&D expenditures and economic growth. The approaches used in these studies cover the full spectrum of methodologies that can be used directly or indirectly in assessing the economic implications of NASA's R&D activities. For purposes of this review, these approaches are classified as follows:

- Aggregate production functions
- Accounting frameworks
- R&D specific models
- Other approaches.

A brief review of each of these areas is presented below. The review includes a general discussion of the approach, the major authors, their quantitative findings, and an evaluation of the applicability of the approach to analysis of NASA's R&D activities.

Aggregate Production Function Estimates

General Approach. The aggregate production function in its most basic form is a statistically derived equation showing the association between growth in total output (GNP or national income) and growth in indices of total capital and total labor adjusted for productivity.* Its original use was in testing economic production theory. Its use for the measurement of technical progress came much later. The basic method for including the effect of technical progress in aggregate production function

* Its mathematical notation is given as $Q = AL^{\alpha}K^{1-\alpha}$, where Q = output, L = labor, K = capital, A = a productivity measure, and α and $1-\alpha$ are the shares of output of labor and capital. This formulation of the aggregate production function is called a Cobb-Douglas function, which originated with the work of Charles Cobb and Paul Douglas in 1928.

estimates is to determine the difference or residual between the total measured growth in output and the growth in output that is directly attributable to increases in the total inputs of capital and labor.* Statistical estimates of this relationship are developed by applying regression analysis to time series or cross-section data. Economic growth that cannot be attributed to growth in the measured inputs of capital and labor is automatically attributed to technical progress.

We have already alluded to the criticism of traditional economic theory for defining "land, labor, and capital" as the three factors of production. To the extent that this criticism is valid it completely destroys the validity of using the traditional Cobb-Douglas production function for any purpose. Both Boulding and Georgescu-Roegen have advanced cogent and persuasive arguments against this definition. Although space does not permit these arguments to be detailed at this point, it is quite obvious that the alternative triad of "know-how, energy, and materials" is pragmatically far more satisfying. It should also be pointed out that even with the traditional framework, most studies that employ Cobb-Douglas formulations use only two of the three alleged factors, generally omitting measurements of "land" inputs as too difficult. Thus, even if their approach were valid, they would be lumping land into their residual and overstating the effect of technology.

Findings of Recent Studies. A variety of studies have been conducted using various mathematical forms of the aggregate production function. The traditional mathematical form is the Cobb-Douglas (as defined above), but more elaborate mathematical functions such as the Constant Elasticity of Substitution (CES) and the Variable Elasticity of Substitution (VES) production functions have been developed.** Since their exposition is not directly relevant to this inquiry, no presentation of their mathematics is included.

* In notational terms this would be $\% \Delta A = \% \Delta Q - \% \Delta Q(K, L)$, where A represents technical progress, Q represents output, and Q(K, L) represent output attributable to increased inputs of capital and labor.

** The concept of elasticity of substitution is an important issue in aggregate production function estimates. Elasticity of substitution refers to the responsiveness of the factor proportion (i.e., ratio of capital to labor) to changes in the relative prices of the factors. The more elastic factor proportions are to relative price changes, the greater the substitution of one factor for another.

Numerous studies using the general techniques of the aggregate production function produce varying results on the role of technical progress in the economy. For example, Solow*, using a modified form of aggregate production function applied to the nonfarm private sector of the American economy for the period 1919-1957, obtains an estimate of annual growth of total productivity of 1.5 percent. This result implies that technical progress (and "land") contributed as much as 90 percent of the rise in real output per man-hour. Use of a CES production function by Solow, Minhas, Arrow, and Chenery for the period 1909-1949 showed annual rates of factor productivity growth of 1.83 percent.** Ferguson, using more recent data (1929-63), found that technical progress accounts for more than 90 percent of the increase in output per man.***

While the aggregate production function has seen extensive use in estimating the rate of technical progress, the approach is not without significant statistical and conceptual problems. Regardless of the specific mathematical form used, studies employing the aggregate production function invariably find technical progress as the prime determinant of economic growth.

Evaluation and relevance to NASA R&D. The aggregate production function has been used extensively to estimate the overall rate of technological progress. Even if its use for this purpose is valid, its direct applicability to the evaluation of NASA's R&D activities is not appropriate. There are two problems which limit its direct applicability. One is the wide variation in results obtained; and the other is its inability to establish the explicit relationships among R&D activities, technical change, and ultimately increases in factor productivity or economic growth.

* Solow, R.M., "Technical Change and the Aggregate Production Function", Review of Economics and Statistics, (August, 1957).

** Arrow, K., H.B. Chenery, B.S. Minhas, and R.M. Solow, "Capital Labor Substitution and Economic Efficiency", Review of Economics and Statistics, (August, 1961).

*** Ferguson, C.E., "Substitution, Technical Progress, and Returns to Scale", American Economic Association Papers, (May, 1965).

The reasons for variation in results using the aggregate production function are outlined by Nadiri.* For example, the magnitude of the residual representing technical progress will depend on:

- The mathematical form of the production function that governs the individual contributions of labor and capital to output
- Proper measurement of labor and capital and adjustments for their quality changes
- Importance of variables other than capital and labor that are left out of the production function.

Whether important factors contributing to growth are left out, qualitative changes in capital and labor inputs are not included, or the production function itself is misspecified, such errors will spill over into the measurement of the residual that represents technical progress. Because of these difficulties, reliance on any one specific quantitative estimate of technical progress estimated from an aggregate production function should be viewed in the context of the uncertainties governing the methodology.

More importantly, there is no way that an aggregate production function approach by itself can facilitate a better understanding of how specific R&D activities have contributed to improvements in factor productivity, to savings in real resource or costs, or to the development of new processes or products which expand our range of choice. This type of analysis requires that each R&D activity be directly linked to a lagged group of innovations--and also that only the part of each separate innovation be ascribed to the particular R&D activity that was derived from the activity, rather than from some other R&D or from general knowledge--and that each innovation, in turn, be similarly linked to subsequent expansions in industry output or sales. Obviously, this is a severely micro, rather than macro, form of analysis that cannot be handled by models as generalized as Cobb-Douglas.

* Nadiri, loc.cit.

Growth Accounting Framework

General Approach. This approach also makes use of the aggregate production function, but uses it as an organizing format within which to examine the factors contributing to economic growth, rather than as a means of estimation. Although approaches using growth accounting formats generally attempt to achieve greater detail in explaining the factors that contribute to productivity increases, they still rely on the residual (i.e., unexplained) growth as their measure of technical change. These approaches utilize index numbers to represent the various factors that are thought to contribute to overall economic growth. The estimation procedure involves detailed analysis and adjustment of the various relevant time series to produce indices of growth or change in the factors that have been identified as contributing to growth. The difference between growth in the index of total output (i.e., the index of GNP or national income) and the index sum that represents all the growths in the factors (other than technological change) that contribute to output is taken as representing the contribution of technology alone.

Findings of Recent Studies. The main authors using this approach are Denison, Jorgenson-Griliches, and Kendrick.

Kendrick uses index numbers of "total factor productivity" based on ratios of net output (real product) to weighted averages of the human (labor) and nonhuman (capital) tangible factor inputs.* The weights represent the shares of factor income accruing to each of the two major factor classes in successive base periods. Labor input is measured in terms of man-hours worked. Capital input is assumed to vary in proportion to the real stocks of tangible capital assets. The inputs are estimated without allowance for changes in their physical productivity, so that changes in the ratios of output to input may be interpreted as reflecting all the diverse forces that affect the quality or productive efficiency

* Kendrick, John W., Postwar Productivity Trends in the United States, 1948-1969, National Bureau of Economic Research, New York, (1973).

of the factors.* For the postwar period (1948-1960), Kendrick finds an annual growth in total factor productivity of 2.3 percent, comparable to the prewar rates. The rates of growth in real product per man-hour and per unit of labor input, however, show further acceleration since World War II, due to a much faster rate of accumulation of capital per unit of labor input than prevailed in the interwar period. Kendrick does not deal with the aggregate effect of R&D, but does explore the relationship in terms of productivity changes by industry. These findings will be discussed below.

Denison's work also relies on an index approach using adjustments for the characteristics of the labor force and magnitudes of capital and labor inputs.** For the labor component of growth, Denison identifies reduction in hours worked, age, sex composition, and the educational quality of the labor force as the main factors affecting labor services. In calculating the residual attributable to advances in knowledge, Denison estimates two sets of contributing factors, each adjusted for economies of scale. The first include changes in employment, composition of employment, level of inventories, nonresidential land, nonresidential structures and equipment, quality of dwelling and residential land, and the quality of international assets. The other set represents adjustment factors due to sectoral misallocation of resources, institutional restrictions, inadequacy of aggregate demand, lags in the adoption of best-practice techniques, and difficulties in the dissemination of knowledge and economies of scale.*** For the U.S., Denison deducted the contribution made to the

* Total factor productivity is defined as $p = \frac{Q}{(aL + bK)}$ where Q, L, and K are respectively the aggregate levels of output, labor, and capital inputs, and a and b are appropriate weights.

** Denison, Edward F., Accounting for United States Economic Growth, 1929-1969, The Brookings Institution, Washington, D.C., (1974).

*** In notational form, Denison's approach is summarized by Nadiri as

$$dQ = \delta \left[\sum_{i=1}^n \alpha_i dX_i + \sum_{j=1}^m y_j + J \right]$$

where dQ is the growth rate of national income valued at 1958 prices, δ is a measure of economies of scale, α_i shows the shares attributable to growth factors dX_i (where dX_i represents growth in the contributing factors), y_j refers to the growth rate of various design factors, and J is the residual attributable to technical change after the total contribution of dX_i and y_j is deducted from dQ.

residual by all sources of growth and attributed the remaining .76 percent to advances in knowledge.

Jorgenson-Griliches take a quite different approach by which the unidentified residual is forced to vanish almost completely.* They start with a calculation of the rate of growth of total factor productivity as an index of the rate of growth in outputs minus a similar index of rate of growth of inputs. Their approach differs from Denison's in the methods of handling the data and making the adjustments, with particular respect to evaluating the contribution of the capital input. Jorgenson-Griliches use capital services rather than capital stock as an input to the production function. Total capital stock is first corrected for biases in deflators of its components, then is adjusted by a trend-like rate of utilization. The substitution of different deflators and the adjustment for the rate of capacity utilization enables them to force the residual attributable to productivity increases to vanish almost completely.

Nadiri has summarized the implications of the Jorgenson-Griliches work**

"...that if inputs and outputs were correctly measured there would be no residual left, is conceptually correct provided all the contributions of growth factors are faithfully reflected in the prices and quantities used in the study."

The conventions used in making these estimates, however, are rather restrictive. Conclusions reached by Jorgenson-Griliches were amended in 1969 by L. R. Christensen with Jorgenson.*** Their calculation differs from that of the Jorgenson-Griliches study by substituting a measure of relative utilization of capital (derived from series on capacity and actual electricity consumption) and by properly separating compensation by legal forms of organization. The results of this effort showed an annual rate of growth of factor productivity of about .31 percent instead of the .1 percent

* Jorgenson, D., and Z. Griliches, "The Explanation of Productivity Change", Review of Economic Studies, (July, 1967).

** Nadiri, p 1168.

*** Christensen, L. R., and D. Jorgenson, "The Measurement of U.S. Real Capital Input, 1929-1967", Review of Income and Wealth, (December, 1969).

shown by Jorgenson-Griliches. More importantly, the authors point out the critical effect that choice of conventions for measuring real factor inputs has on alternative estimates of total factor productivity.

Evaluation and Relevance to NASA R&D. The wide range of results obtained from these studies indicates the variability in estimates of the contribution of technical change that are obtained using various approaches to growth accounting. The extremely low estimates of Jorgenson-Griliches of .1 percentage points (or .3 of Christensen-Jorgenson) contrast with the findings of Denison (.76 percent) and Kendrick (2.3 percent). This wide variation indicates the critical effect on estimates of total factor productivity that arises from choosing among the several conventions for measuring real factor inputs. As Nadiri concludes "...the specific results are too sensitive to changes in the types of data and methods of estimation to provide concrete quantitative figures about the contributions of various factors to the growth of output."*

The growth accounting framework represents a significant step forward in the empirical investigation of factors contributing to increases in total factor productivity. As such, however, it still does not directly aid in understanding the process by which total R&D contributes to overall economic growth, let alone how the R&D of a specific agency or sector of the economy contributes to economic growth.

To the extent that the growth accounting framework utilizes relationships based on the traditional land/labor/capital definition of productive inputs, it is subject to the criticisms already directed to the Cobb-Douglas formulations. Denison, unlike Kendrick, does specifically include "land" in his set of independent variables. Griliches, Jorgenson, and Christensen have adopted a more pragmatic method of dealing with capacity utilization that adds an improvement to the traditional approach, even though it does not overcome its major weakness.

* Nadiri, p 1169.

For analyses of the role of NASA's R&D activities, growth accounting offers little in the way of a specific methodology applicable to the decision and evaluation process. Extension of either the detailed and exhaustive analysis by Denison or the sectorally specific analysis by Kendrick might possibly provide insight into the general role of R&D in the growth of industrial output. Detailed studies of the development and diffusion of technical advances directly or indirectly attributable to past NASA R&D activities (of the type suggested above) would be necessary before we could gain an understanding of the agency's contribution to observed increases in productivity. Whether such analyses could produce valid quantitative relationships, however, is an open question.

Estimating the Contribution of R&D to Economic Growth

General Approach. Several authors have explicitly attempted to estimate the aggregate effect of R&D spending on productivity. To gauge the impact of R&D activity on new knowledge and (ultimately) on growth is incredibly difficult, since there is no unique measure of R&D output which is available for direct use.* Some authors have attempted to measure R&D output in terms of patents. Patents, however, are only one indicator of advances in knowledge. Since invention is a long step removed from the application and diffusion of new knowledge into the production process, the relation, e.g., between R&D and invention reveals nothing about the effect of R&D on the rate of measured technological progress. Still another approach has been to treat R&D activities as a direct input to the production process; many industry specific analyses use this approach. One recent study has attempted to apply estimates of the contribution of NASA R&D to the "residual" (estimated from an aggregate production function) in order to estimate the contribution of NASA's R&D to economic growth. We will examine it later.

* Kennedy and Thirlwall, p 45.

Findings of Recent Studies. Several authors have conducted industry specific studies in which R&D expenditures are correlated with changes in output. For example, Griliches used an aggregate production function (Cobb-Douglas form) including public expenditure on agricultural research as one variable.* This function was fitted through regression analysis to cross sectional data at three different time periods in order to show the effect of R&D expenditure on output. Other authors have examined the effect of industrial R&D on the outputs of various industries.**/** Despite the fact that these studies indicate output elasticities of R&D of about .08 to .12****, the enormous growth of R&D expenditures appears to have had very little impact on the aggregate growth rates for various countries.***** Output elasticity in this context refers to the relationship between expenditures on R&D and changes in the associated value of industrial output. An elasticity of .08 to .12 would imply that for each 1 percent increase in R&D expenditures, the annual value of industrial output would rise by .08 percent to .12 percent.

In similar industrial sector studies, Kendrick experimented with regression analysis to provide a quantitative analysis of the causal factors contributing to productivity increases beyond those suggested by global estimates for the private domestic economy.***** Among the independent variables that he employed were capital stock, variability of output changes,

* Griliches, Z., "Research Expenditures, Education, and the Aggregate Agricultural Production Function", American Economic Review, (December, 1964).

** Mansfield, E., Industrial Research and Technological Innovation: An Economic Analysis, W. Norton, New York, (1968).

*** Minasian, J.R., "Research and Development, Production Functions and Ratio of Return", American Economic Association Papers, (May, 1969).

**** Nadiri, p 1149.

***** Kennedy and Thirlwall, p 47.

***** Kendrick, pp 132-143.

average education per employee, the R&D/sales ratio, average hours worked, industry concentration ratios, rate of change in concentration, and a unionization ratio. The results of this analysis were inconclusive because of the high degree of intercorrelation (termed "multicollinearity" by econometricians) between many of the independent variables. Such intercorrelation makes it difficult to arrive at meaningful multiple regression equations. No conclusive results were obtained with respect to the influence of R&D; but the R&D data themselves were weak, and did not permit the calculation of rates of change in R&D expenditures.

In an earlier macro-analysis, Denison estimated that only 1/12 of the U.S. annual per capita growth rate from 1929-1957 could be attributed to organized R&D.* An important point noted by Denison is that a large part of total R&D effort is devoted to product innovations rather than to improvements in productivity. This helps explain the low contribution of organized R&D to the estimated growth of output.

The meaning of these results for analysis of NASA's R&D activities will be discussed below. Before turning to that, however, attention should be given a recent study focusing specifically on the impact of NASA's R&D expenditures on economic growth. Chase Econometrics, Inc., investigated the impact of NASA R&D spending on the U.S. economy.** This study attempted to show both the effect of increased spending on total demand and the effect of a higher rate of technological growth on total supply (via higher total productive capacity). The authors found that the demand effects were of short-term nature, the supply effects on aggregate economic activity supposedly not being significant until the fifth year after expenditures had increased. This analysis attempted to relate the rates of technological progress in a number of factors (including R&D spending) that had been chosen to represent the determinants of increases in productivity. They used a standard (Cobb-Douglas) aggregate production function with a variable

* Denison, E.F., The Sources of Economic Growth in the U.S. and the Alternatives Before U.S., Committee for Economic Development, New York, Library of Congress, (1962).

** The Economic Impact of NASA R&D Spending (Prepared under NASA Contract NASW-2741, April, 1975). Only the "Preliminary Executive Summary" of this report was available for use in this critique. Although it does not provide full details of the statistical manipulations that were made, it does permit consideration of the methodology.

for technical progress. After adjusting output figures to reflect maximum output potential and estimating the amounts of growth attributable to capital and labor inputs, regression analysis was used to determine the "residual", or rate of technical progress. An equation explaining the rate of technical progress was then developed with independent variables that included lagged R&D spending (with NASA and other industry R&D separately expressed as percentages of GNP), an industry-mix variable, an index of capacity utilization, and an index of labor quality.* Applying this methodology to time series data for 1960-74, the authors found that, starting in 1975, a \$1 billion increase in NASA's R&D spending would result in a \$4.26 billion constant dollar increase in GNP by 1984, with the increases beginning in 1979 at a rate of \$260 million per year. When translated into a rate of return calculation, this resulted in an estimated 43 percent return on investment. Since such estimates would indicate a very high payoff to NASA's R&D activity, it is especially important that we examine the methodology carefully.

Evaluation and Relevance to NASA R&D. The several methodologies to be evaluated can be treated in terms of the industry-specific analyses, taken together, and the macroeconomic analysis of Chase.

The industry-specific studies are attempts to isolate the impacts which R&D may have on the factor productivities of various economic sectors. It is not certain whether the relationships between R&D and sector output established by such studies are those of causality or correspondence with other industry characteristics. As such, these general relationships

* In notational form, this methodology would be described as follows:

$$dQ = dK + dL + T \quad \text{or} \quad T = dQ - dK - dL$$

$$dT = \sum_{i=1}^n dA_i$$

where dQ , dK , and dL are rates of change in total output, capital, and labor, T is the residual attributable to advances in knowledge (or technical change), and dA_i are the changes in the independent factors thought to influence change in the magnitude of the residual.

between R&D and output are not directly relevant to NASA R&D without specific knowledge both of how past NASA-related technological changes have diffused into the economy and of which industrial sectors have been most affected. Detailed studies in this area would be more directly useful than would repetitions of econometric sectoral studies of independent variables (including R&D) which may influence differential rates of productivity growth. The one exception to this conclusion would be the case if and where good time series data on industry R&D could be obtained.* In this case, extension of previous industry-specific analysis could be of indirect benefit to an evaluation of NASA's R&D activities, providing that there has been an understanding of how NASA R&D has affected these sectors in the past.

Although the macroeconomic analysis of Chase Econometrics, Inc., is an interesting application of econometrics to available data, the results depend significantly on three critical relationships. The first is the (perhaps questionable) validity of estimating the influence of technical change through the aggregate production function and the residual; the second derived from the previously discussed criticism of the traditional definition of factors of production; and the third involves the use of specified independent variables to explain the rate of technical progress or change.

As was discussed previously, specific quantitative estimates of the role of technical change are subject to considerable variability depending on the mathematical form used and on the methods of handling the data. Some critics have argued that what is called technical progress

* Since the 1974 adoption by the Financial Accounting Standards Board of Standard #2 on accounting for R&D, there is a growing probability that useful time series on industrial R&D can be developed. The Forms 10-K, which all public corporations must file annually with the Securities & Exchange Commission (SEC), have required separate reporting of R&D expenditures since 1970. Before the adoption of Accounting Standard #2, however, each company used its own definition of R&D and the data were meaningless on any aggregate basis. Hopefully this has now been changed. (Business Week (June 28, 1976), see pp 62 ff.)

in this context may not be technical progress at all, or even advances in knowledge, but rather the composite result of:

- Substitution of capital for labor
- Economies of scale
- Effects of the "learning curve"*
- Increased education
- Resource shifts
- Organizational improvements.

The earlier footnote and related text setting forth the notation of the Chase Econometrics model for NASA R&D expenditure shows the first equation of the model to be a Cobb-Douglas production function. The variables of this function are in the standard labor/capital definition and are therefore subject to all the weaknesses ascribed by Boulding to this definition.

Turning now to the second equation of the Chase model, even after we assume that the influencing of technical progress on economic growth has been correctly measured, any specification of independent variables as governing the rate of technical progress is fraught with statistical and conceptual problems. For example, how do we know that the independent variables assumed to influence technical progress include all the important influences? And then, to what extent are the specified independent variables so significantly intercorrelated that the addition or removal of single variables would dramatically affect the estimated coefficients.** Finally, does the single equation adequately explain the relationships governing technological change, or are there simultaneous effects which have been overlooked? These points do not invalidate the Chase analyses, but they are important considerations in evaluating the reliability of the quantitative results obtained from such estimating

* Thurow, op.cit., points out that the "learning curve"--the cost-reducing role of industrial experience with any innovation--is a very important technological force and implies that it probably does much to explain the connection between innovation and its social impacts.

** This is the classical problem of multicollinearity or high correlation between independent variables.

techniques, and they have not been dealt with explicitly in the material available to us. More importantly, even if the model is correctly specified and estimated, estimation of future effects of specific (NASA) micro-R&D on productivity based on historical macroeconomic relationships can only be viewed with considerable skepticism.

Other Analytical Frameworks for Assessing R&D

While the above studies have primarily focused on quantitative macroeconomic relations, a major concern in assessing the effects of R&D are the microeconomic relationships which may ultimately produce macroeconomic effects. Thurow has proposed a general overview of the process of assessing public R&D projects that focuses on the problems of uncertainty and noncomparability between different public R&D alternatives.* He suggests the use of benefit/cost framework for assessing R&D alternatives within a research area, but not the use of formal benefit-cost analysis. He suggests establishing judgmental ranges of the benefits and costs associated with commensurate R&D projects along with a maximum potential benefit level for each. These estimates should be developed by more than one individual or group, given the uncertainties inherent in such exercises, and point-estimates should not be used for decision purposes. He suggests four categories of R&D for purposes of public analyses:

- National independence (defense, space, foreign affairs, and intelligence)
- Lifesaving (health, safety, wartime casualties, and environment)
- Economic goods and services
- Noneconomic, quality-of-life goods and services.

This categorization is intended to provide comparisons across as wide an area as is feasible and each of the areas suggests an internally consistent "unit of measure". While Thurow's format is focused on a somewhat different problem than the other studies reviewed here, it is included because of its

* Thurow, op.cit.

direct applicability to the evaluation of specific mission-oriented R&D activities such as those regularly undertaken or funded by NASA.

Whether or not Thurow intended it, the proposals made in his paper are the kind that would be of especial relevance to NASA. All three categories of R&D that he suggests (basic-capabilities, mission-oriented, and massive mobilization) seem to fit well the projects funded by NASA. Although most of NASA's R&D activities probably fall into the first two of the above four functional classes (national independence and lifesaving), the other two are well represented, especially with respect to specific technological possibilities. Finally, the analytic method he proposes (use of the benefit/cost framework and judgmental ranges) is uniquely applicable to NASA activities, even though more fully quantified evaluations probably will be impossible. NASA could undertake a very full program of R&D evaluation using this methodology, probably at quite reasonable levels of cost.

Of the approaches and methodologies reviewed, the framework proposed by Thurow appears to have the greatest potential for aiding NASA in the evaluation of ongoing or planned R&D projects. The suggested estimation of the maximum potential benefits of specific R&D activities requires an analysis of the ways in which potential technologies that may result from each NASA project may be diffused to or adopted by other sectors of the economy. This also requires an analysis of the types of resource savings or productivity gains that a potential technological development will spawn. In contrast to other more general analyses of total factor productivity or of sector specific R&D effects, the benefit-cost framework forces the analyst to be forward looking rather than extrapolating historical relationships.

In contrast, the approaches that have been followed all depend on the use of Cobb-Douglas production functions in highly aggregated macroeconomic analyses. Not only is this approach far too aggregative to give meaningful results when applied to a reality composed largely of lagged micro-relations, but the subject applications all operate in terms of questionable definitions of the factors of production. One cannot but feel that, aside from incidental refinements in statistical methods, these attempts at quantifying relationships between R&D, innovation and/or technology, on the one hand, and economic growth, on the other, are sterile.

FINDINGS CONCERNING PAST STUDIES

Aside from Thurow's proposed (essentially noneconometric) analytic framework, the econometric approaches that have been employed in examining economic growth and the role of R&D in technical change have all relied on the concept of the aggregate production function. The production function concept involves estimation of the influence of growth in two factors, namely, capital and labor, on economic output. Whether the production function is used formally to estimate increases in factor productivity or is used as an accounting framework, the role of technological change in productivity is estimated as a residual after accounting for the direct (adjusted) inputs of labor and capital.

Approaches using growth accountancy attempt greater detail in explaining contribution to increases in factor productivity, but they still rely on the residual or unexplained growth as their measure of technological change. Lacking in both of these variants of the aggregate production function is a meaningful understanding of how R&D contributes to technical change and to economic growth. The specific estimates of R&D relationships focus primarily on inter- and intra-industry effects, with the one exception of the Chase study. The potential shortcomings of this latter approach are serious and already have been examined.

When we take into account the definitional and conceptional inadequacies of all these studies, they must all be taken with a considerable degree of skepticism. The general failure of the econometric approach--especially that which relies on the use of some form of Cobb-Douglas formulation--can best be summarized by a direct comparison of their findings. In order to provide this comparison, we have taken the liberty of successively substituting the Cobb-Douglas-based growth rates of a group of the earlier studies into that portion of the Chase results. Each of these several studies dealt with a different period of time, used different statistical data, and manipulated them in different ways. It is therefore impossible to reduce them to full compatibility or comparability. Nevertheless,

the following very approximate comparison gives some indication of the great range of results--too great to be useful or to lend credence to any of the individual studies--that to which the Cobb-Douglas approach gives rise.

We have taken the several estimates of the "residual", summarized in the first full paragraph beginning on page 15, above, and substituted them in the Chase equations for the "residual" that Chase had obtained. By this manipulation we express each set of findings in direct contrast to each other and to the 43 percent return on NASA R&D activity found by Chase. The several values of the "residual" are:

Jorgenson-Griliches:	0.10%
Christensen-Jorgenson:	0.30%
Denison:	0.76%
Chase:	1.30%
Kendrick:	2.30%

Fully realizing that some of these residual values are not directly comparable with others, we divide each of them by the Chase value and multiply the quotient by the Chase return on investment (43%). Thus, for Jorgenson-Griliches, the computation is:

$$0.10/1.30 \times 43\% = 3.31\%$$

This manipulation gives rise to the following set of ROI's:

Jorgenson-Griliches:	3.31%
Christensen-Jorgenson:	9.92%
Denison:	25.14%
Chase:	43.00%
Kendrick:	76.08%

It will be recalled that the Chase study found that a \$1 billion increase in NASA R&D, beginning in 1975, would give rise to a \$4.26 billion increase in GNP by 1984. If we apply the same factor of increase to the other residuals, the comparison would look like this:

Jorgenson-Griliches:	\$0.33 billion
Christensen-Jorgenson:	0.98 "
Denison:	2.49 "
Chase:	4.26 "
Kendrick:	7.54 "

Again, we realize that there may be elements of "apples vs. oranges" in this comparison. Nevertheless it is indicative; and it suggests that policy decisions cannot be made safely with this kind of analysis.

SOME RECOMMENDATIONS FOR FUTURE NASA STUDIES

Nadiri has summarized the major directions that future analyses of the contribution of technological change to economic growth must pursue, even if approached in traditional terms. Of particular importance is the formulation of an alternative system of accounting which registers both the utilities provided by conventional inputs (labor and capital) and those provided by other factors such as natural resources, physical environment, human skill and knowledge, social and political structures, etc. Such an approach requires concentration on much more disaggregative studies, such as the use of microeconomic production functions, interindustry (or input-output) models, resource allocation models, and a variety of other sector-specific methodologies.

In terms of possible directions for NASA's R&D evaluation efforts, three distinct areas appear especially relevant. One involves the examination of NASA's past R&D and how it has affected the productivities in specific sectors of the economy. The second involves an extension of the benefit-cost framework proposed by Thurow to the evaluation of ongoing or planned NASA R&D activities. The third requires an integration of all kinds of R&D activity into an interindustry (I/O) model which would then be used for a series of simulations. Each of these possibilities is explored briefly in the concluding portion of this report.

Proposed Detailed Analyses of NASA-Related Technological Changes

The emphasis here would be on tracing the processes and paths by which NASA-generated innovations have been diffused to industry and the specific microeconomic impacts that they have had on production and consumption. It would be important in this type of undertaking first to examine the role NASA R&D has played in the process: how existing knowledge

has been expanded through NASA's activities to produce specific technical advancements. Second, those sectors of the economy that ultimately adopted each technical advance would be identified to the fullest extent practicable and the effects of the separate innovations on production processes, capital formation, products or inputs traced in detail. Finally, economic analyses of the effects on each sector's output or growth should be explored, using whatever economic tools are most appropriate to available data and to the problem.

By carrying out or sponsoring this type of exercise for several identifiable innovations NASA would obtain more explicit knowledge of how selected types of R&D projects have influenced the economy than can be obtained by any other approach. This type of information would be useful in underpinning or evaluating other studies of the aggregate impact of NASA activities.

Benefit-Cost Framework

The benefit-cost framework proposed by Thurow could profitably be extended to include the potential spillover effects of NASA's R&D on the general economy. Such an extension would require detailed evaluation of potential industry or public sector adaptations that could ultimately occur as a result of specific NASA research or that might be forced by the indirect effects (externalities) of particular NASA-related innovations. For each potential adaptation, the maximum possible annual benefit should be estimated, with appropriate ranges to encompass the tremendous uncertainties inherent in such estimates. Very important in the benefit estimates would be analyses of what each expected innovation might accomplish--e.g., is it a true resource saving? does it allow greater output from a given set of resources? does it result in new materials or products which substitute for existing materials? to what secondary or derived demands for other resources (particularly energy) will adoption of the technology lead? After maximum benefits and ranges of benefits have been approximated, total expected cost ranges for NASA investment in the specific R&D project and the ranges of expected private-sector adoption costs would need to be

approximated for each specific R&D project or group of projects. Comparison of maximum benefit and possible range of benefits to cost ranges would provide a guideline on the merits and potentials of any specific R&D activity.

R&D in the Interindustry Model

The integration of specific information concerning R&D into modified input-output models provides a potentially fruitful approach to the contribution of R&D to economic growth. Utilizing data being made available by the National Science Foundation and by the SEC's Forms 10-K, it should be possible to determine the customary levels of purchase (or provision) of R&D by each industry sector and by each segment of final demand (especially governments). When manipulated in the simulation mode, such a model can throw a great deal of light on the economic impacts associated with the funding and use of R&D.

To the extent that R&D leads to technological change in particular industries, these changes can be entered into simulations (in the form of scenarios) and their impacts also estimated. Thus, when used imaginatively as a simulation model, rather than as a statistical exposition of past surveys, the interindustry table becomes a powerful analytic tool. Unfortunately, the conventions followed in constructing many of the best known of these tables render them useless for this purpose without careful reconstruction.